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**EVALUATION OF THE  
MICHIGAN DEPARTMENT OF ENVIRONMENTAL QUALITY'S  
GENERIC GROUNDWATER AND SOIL VOLITIZATION  
TO INDOOR AIR INHALATION CRITERIA**

*(A Science Report to Governor John Engler)*

*Prepared by  
Michigan Environmental Science Board  
Indoor Air Inhalation Panel*

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**MAY 2001**

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## **PREFACE**

### **Michigan Environmental Science Board**

The Michigan Environmental Science Board (MESB) was created by Governor John Engler by Executive Order 1992-19 on August 6, 1992. The MESB is charged with advising the Governor, the Natural Resources Commission, the Michigan Department of Natural Resources and other state agencies, as directed by the Governor, on matters affecting the protection and management of Michigan's environment and natural resources. The MESB consists of nine members and an executive director, appointed by the Governor, who have expertise in one or more of the following areas: engineering, ecological sciences, economics, chemistry, physics, biological sciences, human medicine, statistics, risk assessment, geology and other disciplines as necessary. Upon the request of the Governor to review a particular issue, a panel, consisting of MESB members with relevant expertise, is convened to evaluate and provide recommendations on the issue. The MESB is neither a state policy body nor an advocate for or against any particular environmental or public health concern.

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*Evaluation of the Michigan Department of Environmental Quality's  
Generic Groundwater and Soil Volatilization to Indoor Air Inhalation Criteria*

**Major Findings and Conclusions**

The Michigan Department of Environmental Quality (MDEQ) has been engaged in development of generic cleanup criteria to implement the provisions of Part 201, Environmental Remediation, of the Natural Resources and Environmental Protection Act, 1994 PA 451, as amended (Part 201). The MDEQ has identified inhalation of volatile hazardous substances that migrate into indoor air from contaminated soil and groundwater as a relevant exposure pathway. Field experience supports the concept that vapors will move passively through soil and be drawn into interior spaces because of the pressure differentials that exist in the two environments. In addition, there is evidence published in the scientific literature that supports soil-gas transport and entry into buildings as a common phenomenon (i.e., volatile hazardous substances move as a gas through soil and building foundations and enter habitable spaces).

On October 29, 1999, Governor John Engler requested that the Michigan Environmental Science Board (MESB) evaluate the MDEQ's approach to evaluating indoor inhalation exposure pathway risks at sites of environmental contamination - as described in the document entitled, *Part 201 Generic Groundwater and Soil Volatilization to Indoor Air Inhalation Criteria, Technical Support Document (TSD)* - and determine whether it provides a scientifically and technically defensible strategy for the development of generic cleanup criteria for this exposure pathway. A Panel, composed of four MESB members and one guest scientist, was assigned to address the Governor's request. The investigation consisted of the accumulation and evaluation of peer-reviewed and some non peer-reviewed literature and data on the subject. In addition, verbal and written testimony from experts, state regulatory agencies, environmental organizations, and concerned citizens was considered at four meetings. The major findings and conclusions of the MESB report are summarized below.

◆ Situations in which the volatilization of contaminants in soil or groundwater to indoor air is the major exposure pathway are rare. Generic criteria developed for chemical contaminants using this pathway of human exposure must be based upon accurate science with carefully selected physical, chemical, and transport properties, and must be extensively field tested to ensure that they are protective of public health on the one hand, but avoid a preponderance of false positives on the other. The Panel concludes that the choice of the Johnson-Ettinger Model (JEM) as the model for the calculation of such generic criteria in the MDEQ TSD is appropriate. The model is consistent with its intended generic use; its foundation is based in sound science, and it is widely accepted by other regulatory agencies including the U.S. Environmental Protection Agency (USEPA). It is recommended by the American Society for Testing and Materials to guide corrective actions at petroleum release sites; and it is computationally and parametrically straightforward to use. In addition, the calculational simplicity and excellent documentation in the choice of the JEM allow ease of site-specific modification of the generic criteria should a property owner desire to adapt the generic criteria to better represent actual facility conditions. There are currently no other competing models in common use that are not derived from the JEM.

◆ Because it models a complex problem, the JEM requires an unusually large number of input parameters. The values of some of these parameters may vary over a wide range, resulting in widely varying output predictions. Thus, the use of field-derived data and data from more controlled studies is required to: (1) demonstrate the applicability and validity of the JEM for the prediction of site-specific conditions and (2) confirm the selection of generic input parameters. The Panel concludes that neither under field nor more controlled conditions has a thorough validation of the model been obtained. Consequently, it would be useful for both the USEPA and the MDEQ to orient their extensive data collection at relevant sites to providing data that can be used for validation of the model and generic input parameters used in Michigan. As presented in this report, the MDEQ JEM can be used to generate indoor air contaminant concentrations to correlate with actual data.

◆ Although slightly different, the input parameters chosen by the USEPA and the MDEQ for use with the JEM appear to be defensible to produce generic criteria that would be protective of public health and that would identify only those contaminant site situations that may require deed restrictions, engineering

controls, further site cleanup, or a combination of remedial techniques. However, the Panel remains concerned that sufficient data are not available at this time to fully assess whether the input parameter values selected by the MDEQ for use in the JEM are appropriate choices for the development of generic criteria. The data generated from the Chatterton, Massachusetts, Colorado, and MDEQ studies, while important to this evaluation, are currently too limited for the Panel to reach a definitive conclusion. Despite the above, the Panel reaffirms the JEM as the method of choice for evaluating indoor inhalation exposure pathway risks and advises the continued effort to obtain sound scientific field validation to guide the application of the algorithm.

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## **Introduction**

The Michigan Department of Environmental Quality (MDEQ) has been engaged in development of generic cleanup criteria to implement the provisions of Part 201, Environmental Remediation, of the Natural Resources and Environmental Protection Act, 1994 PA 451, as amended (Part 201). In 1995, amendments to Part 201 were enacted that require the MDEQ to use reasonable and relevant exposure pathways in developing generic, land use based cleanup criteria. The MDEQ has identified inhalation of volatile hazardous substances that migrate into indoor air from contaminated soil and groundwater as a relevant exposure pathway. Since early 1997, the MDEQ has been working on development of scientifically sound generic cleanup criteria for indoor air contaminants attributable to migration from environmental contamination. The MDEQ's field experience supports the concept that vapors will move passively through soil and be drawn into interior spaces because of the pressure differentials that exist in the two environments. In addition, there is evidence published in the scientific literature that supports soil-gas transport and entry into buildings as a common phenomenon (i.e., volatile hazardous substances move as a gas through soil and building foundations and enter habitable spaces) (Hers *et al.*, 1999; API, 1998; Hers and Zapf-Gilje, 1998b; Fischer and Uchirin, 1996; Fischer *et al.*, 1996; Garbesi *et al.*, 1993; Little, Daisey and Nazaroff, 1992; Hodgson *et al.*, 1992; Mosely and Meyer, 1992; Shoemaker and Lion, 1991; Garbesi and Sextro, 1989; Culver; and Nazaroff *et al.*, 1987). The MDEQ has proposed administrative rules that describe conditions under which the indoor inhalation pathway is deemed relevant and that set forth algorithms for calculation of generic criteria.

## **Charge to the Michigan Environmental Science Board**

On October 29, 1999, Governor John Engler requested that the Michigan Environmental Science Board (MESB) evaluate the MDEQ's approach to evaluating indoor inhalation exposure pathway risks at sites of environmental contamination - as described in the MDEQ (1998) document entitled, *Part 201 Generic Groundwater and Soil Volatilization to Indoor Air Inhalation Criteria, Technical Support Document* (TSD) (see Appendix 1) and determine whether it provides a scientifically and technically defensible strategy for the development of generic cleanup criteria for this exposure pathway (Engler, 1999; see Appendix 2).

## **Michigan Environmental Science Board Response**

A Panel, composed of four MESB members and one guest scientist, was assigned to address the Governor's request. The investigation consisted of the accumulation and evaluation of peer-reviewed and some non peer-reviewed literature and data on the subject. In addition, verbal and written testimony from experts, state regulatory agencies, environmental organizations, and concerned citizens was considered at four meetings (Harrison, 2000a; 2000b; 2000c; 2000d). The report was prepared by the Panel with each member assigned a specific topic or topics to address.

## Description of Mathematical Model and its Assumptions

The basis of the MDEQ model for evaluating migration of contaminant vapors to indoor air is the mathematical model developed and presented by Johnson and Ettinger (1991). This Johnson and Ettinger model (JEM) was selected based upon its computational and parametric simplicity, its foundation in sound science, its widespread acceptance by other regulatory agencies and the ease in which model parameter values can be modified for development of facility-specific criteria. For example, the JEM is described in the U.S. Environmental Protection Agency's (USEPA) guidance documents for assessing potential air impacts at Superfund sites (USEPA, 1993; 1992) and for soil screening (USEPA, 1996), and is used by the American Society for Testing and Materials (ASTM) to guide risk-based corrective actions at petroleum release sites (ASTM, 1995).

The JEM is based upon a one-dimensional analytical solution to an equation describing contaminated vapor transport in the subsurface. Its output is an *attenuation coefficient* that represents the ratio of the vapor concentration in the indoor air space in a building to the vapor concentration at the source of contamination (i.e., soil or groundwater). The model is the direct computational link between the measured soil or groundwater contaminant levels and the predicted contaminant exposures for indoor air inhalation.

The modeled scenario is conceptually depicted in Figure 1. Contaminated soil or groundwater underlies a residential or commercial building at a specified depth. The foundation slab lies at a known elevation below grade. Contaminant vapors migrate from the source zone under the action of molecular diffusion (in the soil gas and soil water phases) and are then swept into the building through foundation cracks of a specified area. The building ventilation system and meteorological factors induce the pressure differential that creates this advective flow of vapor from the surrounding soil into the building. The flux of contaminant into the building is computed by matching the diffusive flux from the contaminant source within the subsurface with the flux induced by advection in the vicinity of the foundation. The resultant indoor air concentration is then computed from the incoming mass, the volume of the building, and the specified building air exchange rate.

The JEM incorporates a number of simplifying assumptions. Perhaps the most significant is the assumption of reduced dimensionality. The scenario depicted in the figure is idealized as a one-dimensional system. Fluxes from contaminant sources move vertically upward, directly into the building above. Thus, all vapor contaminants that reside within the "footprint" of the building will eventually enter in the building. Furthermore, the source region is assumed to extend uniformly under the entire building foundation area, i.e. this entire area contributes contaminant mass. Because diffusive transport is assumed to be vertical, lateral migration of vapor contaminants from outside of the footprint area of the building is neglected. In general, this reduced dimensionality is a conservative assumption.

A second important model assumption is that of steady transport conditions. As a consequence of this assumption, simple analytical solutions are employed in the JEM to describe contaminant fluxes within the soil zone and through the foundation cracks. This assumption implies that the contaminant source is not depleted over time. Any seasonal variations in building ventilation rates are also neglected. The steady transport assumption is reasonable, given that long time (yearly) contaminant flux averages are desired. In general, this assumption is conservative, as long as selected model parameters are consistent with yearly (time-averaged) values.

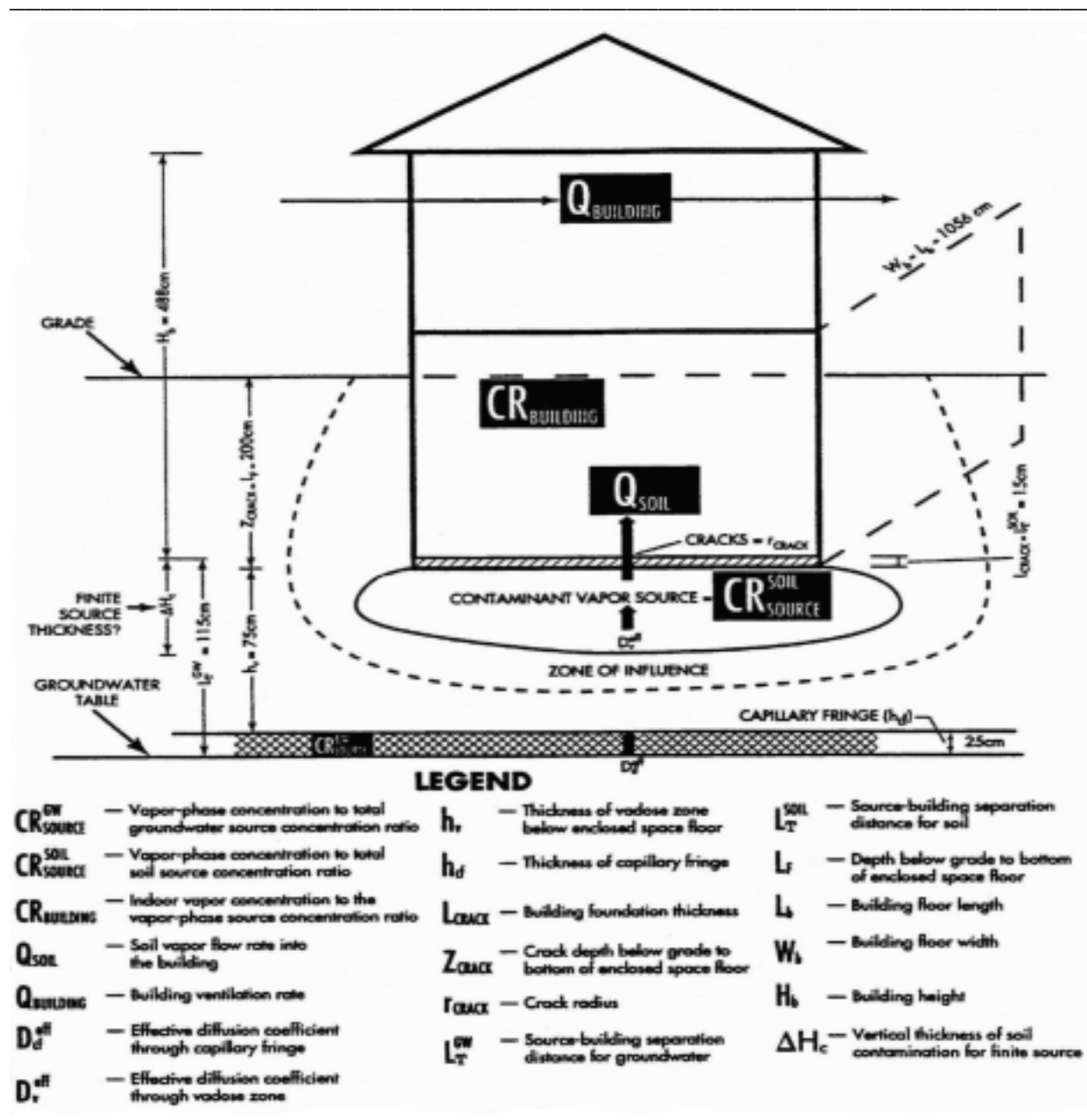


Figure 1. Residential Vapor Intrusion Conceptual Site Model (from MDEQ, 1998).

A third model assumption is that of subsurface homogeneity. The volume of soil beneath the building is assumed to have uniform geological, hydrological, and chemical properties. In particular, soil type permeability, moisture content, and organic carbon content are assumed to be constant within this region. Although this assumption is an over-simplification of most field conditions, it is reasonable for the intended generic application, particularly in the absence of detailed field measurements.

A fourth general model assumption is that of local thermodynamic equilibrium. Application of this assumption allows the contaminant concentration at a particular spatial location in any subsurface compartment (water, air, or soil) to be related to the mass in every other compartment at the same location by partitioning relations (Henry's law, linear sorption isotherm). This assumption will result in conservative predictions of contaminant fluxes; that is, deviations from local thermodynamic equilibrium tend to decrease the magnitude of transported concentrations.

The building configuration, foundation crack geometry, and source zone location and geometry are important model inputs. Some of the more significant of the geometric input parameters are the source-building separation distances ( $L_T$ ) (see Appendix 1). For the soil volatilization scenarios selected for development of the generic criteria, the contaminated soil zone is assumed to lie immediately beneath the foundation. This assumption tends to make building ventilation (pressure differential) the predominant driving force for contaminant transport into the building. For development of the generic groundwater criteria for indoor air inhalation, a shallow water table is assumed (at a depth of three meters for the residential case). In general, the more shallow the water table, the larger the predicted diffusive transport of contaminants from the groundwater to the building. Thus, this tends to be a conservative assumption for most real scenarios.

Conceptually, the JEM can be described as a series of calculations or steps. Each of the calculations is described below and the relevant equations are referenced in Appendix 1. The referenced equations in Step 1 have been modified from the JEM by the MDEQ in Appendix 1 for purposes of back-calculating criteria.

*Step 1. Computation of the vapor concentration at the contaminant source (Equations 6 & 7: Generic Groundwater to Indoor Air Inhalation Criteria - GVIIC and Soil Volatilization to Indoor Air Inhalation Criteria – SVIIC).*

In this step, the total contaminant concentration in the soil (as measured analytically from soil core samples) is used to estimate the vapor phase concentration in the source region. As explained above, linear equilibrium partitioning relations are assumed. The partitioning coefficients are chemical-, temperature-, and soil-specific. Both temperature and soil type are fixed for model use in the development of generic criteria. Under these conditions, the vapor phase concentration is determined solely by the properties of the contaminant. For the groundwater generic criteria, the equilibrium vapor concentration is determined directly from Henry's law coefficient at the groundwater temperature and the groundwater concentration.



### *Step 2. Calculation of diffusive flux through the soil.*

In this step, diffusion is represented by a linearization of Fick's law of diffusion. This linearization is valid under the steady flux and homogeneous soil and groundwater conditions of the modeled generic scenario. Diffusion within both the water and vapor phases is considered, although the former is approximately four orders of magnitude smaller than the latter under most conditions. Surface diffusion is neglected in the model. The dependence of the effective diffusion coefficient on soil moisture content is described according to the Millington-Quirk expression (Millington, 1959), an empirical correlation that has been widely used and tested in the soil science literature (Equation 9: SVIIC, GVIIC). For the calculation of the effective diffusion from the saturated groundwater zone (for the groundwater generic criteria), the diffusion path is divided into two sections or layers of known thickness, the capillary fringe and the soil unsaturated zone. An average moisture content within the capillary fringe is computed from an assumed moisture retention curve for the soil, evaluated at the air entry pressure. The selected moisture retention curve has the functional form suggested by van Genuchten (1980) and is widely used in the contaminant hydrology field (Equation 12: GVIIC). In accordance with the concept of resistors in series, the effective diffusion coefficient is then evaluated as the geometric mean of the effective diffusion coefficient in each layer (Equation 10: GVIIC).

### *Step 3. Transport of Vapors into the Building.*

Transport of contaminants into the building from the soil gas is assumed to occur by both advective (vapor flow) and diffusive mechanisms. Thus, the contaminant flux is a function of both the volumetric flux through the foundation cracks (induced by pressure differentials) and the diffusive flux induced by the difference between the soil vapor concentration immediately adjacent to the foundation and the indoor air concentration. The zone of influence of the building ventilation is assumed to be confined to the immediate vicinity of the foundation. The volumetric flux is computed using an analytical solution for steady flow to a cylindrical crack (Equation 15a: SVIIC, GVIIC), where the velocity is governed by a modified Darcy law expression. The foundation walls and slab themselves are assumed impermeable and any vapor density contrasts are neglected. Both are reasonable assumptions under pressure driven flow conditions. In accordance with the application of the modified Darcy law, the magnitude of the volumetric flux is proportional to the effective soil vapor permeability (Equation 19: SVIIC, GVIIC), which is the product of the soil intrinsic permeability (Equation 16: GVIIC, GVIIC) and the relative permeability to the gas phase. The modified Darcy law is the accepted equation for the description of gas flow in a multiphase porous medium and is widely used in soil science, hydrology, and petroleum engineering. In the MDEQ model, the relative permeability is described with a van Genuchten functional form (van Genuchten, 1980) (Equation 17: GVIIC, SVIIC), evaluated at a prescribed uniform soil moisture content (Equation 18: SVIIC, GVIIC). The van Genuchten form is one of two commonly used representations of relative permeability in the multiphase literature. For the diffusive component of the flux, diffusion within the foundation cracks is governed,

as in the soil zone, by Fick's law. The cracks are assumed to have the same effective diffusion coefficient as the surrounding soil. This implies that the cracks are filled with soil of the same moisture content. Based upon this mathematical model, the most sensitive parameters for the calculation of the flux into the building are the soil permeability ( $k_v$ ) the applied pressure differential ( $\Delta P$ ), the depth of the foundation below grade ( $Z_{crack}$ ) and the crack area ( $A_{crack}$ ). All are prescribed in the selected generic scenarios.

#### *Step 4. Calculation of an attenuation ratio.*

In this step, the model computes the ratio of the indoor air concentration to the source zone vapor concentration. This ratio is known as the attenuation coefficient. It is calculated by first invoking the steady flow assumption and setting the fluxes, computed from Steps 2 and 3, equal to each other. This results in an expression for the soil vapor concentration immediately beneath the foundation. A mass balance is then written for the steady flux of contaminant into and out of the building, yielding a final expression for the attenuation coefficient, given by Equation 8 (GVIIC, SVIIC). This expression explicitly incorporates the building ventilation rate (defined by Equation 14: GVIIC, SVIIC).

#### *Step 5. Calculation of the GVIIC or SVIIC.*

In this final step, the acceptable soil or groundwater concentration is back calculated from the attenuation coefficient and the acceptable indoor air concentration. The latter is computed as a function of specific exposure assumptions and the toxicity characteristics of the contaminant (Equations 1 and 2: SVIIC; Equations 3 and 4: GVIIC).

### **Discussion of Input Parameters and Assumptions**

The input parameters for the equations in the model are detailed in the MDEQ (1998) TSD (Appendix 1), and need not be repeated here. The JEM requires detailed specifications about the building size, crack area, ventilation rate, and the pressure differential. All of these parameters are highly variable from site to site. Soil properties, such as the water and air content, and specific chemical and transport properties of the contaminants must be estimated. The generic building volume for both residential and commercial buildings chosen by the MDEQ are clearly small and conservative. The MDEQ has documented all of its decisions and rationales for choosing the input parameter values employed in the calculation of the generic criteria. Depending on the calculation, 50 to 100 parameter values are required. Even at this level of complexity, the model simplifies reality in a number of ways. The JEM is one-dimensional and assumes steady state conditions, homogeneous soil properties, and local thermodynamic equilibrium. All of these assumptions tend to cause the JEM to over-predict the actual contaminant concentration in indoor air relative to the soil/groundwater concentrations for most realistic conditions.

The JEM does not consider movement of the contaminant downward, nor does it consider degradation or transformation of the source contaminant. To the extent that these phenomena happen, the JEM is likely to over-predict the actual indoor air contaminant concentrations. On the other hand, the JEM assumes that the building contains no other sources of the contaminant and neglects contributions from the ambient air, which could augment the actual concentrations. It also does not account for preferential flow paths that may exist due to buried utilities, roots, burrowing animals, and dryer soil beneath the building. The JEM assumes instantaneous mixing within the building, and hence uniform in-building concentrations. Reality would suggest some gradients, implying that concentrations near the basement would exceed the JEM predictions and concentrations at remote points would be lower than the JEM predictions.

In view of the many assumptions incorporated into the development of the generic criteria, the Panel felt that the model should be validated for real cases meeting its basic assumptions, and searched for studies that would provide some confidence in the values predicted. Two types of studies have been performed by previous researchers in the discipline: sensitivity studies, which examine the reliability of the final predictions as a function of the uncertainty of the input parameters, and field studies, which use the model to compare predictions with actual results under comparable conditions.

**USEPA Sensitivity Analysis.** The USEPA (1996) contracted for a sensitivity analysis of its version of the JEM, which contains the USEPA selected generic input parameters, which differ slightly from those selected by MDEQ, and which includes both a finite source and an infinite source. Consequently, conclusions regarding the sensitivity of the USEPA version are not always applicable to the MDEQ version of the JEM, but are certainly illustrative of the behavior expected. The USEPA study illustrated the complex nature of the sensitivity of the output predictions to the input parameters, largely because of the change from convective control to diffusion controlled behavior for differing chemical properties and site geometries. Variables found to be important in some regimens include the soil permeability to vapor flow, the soil building pressure differential, the depth of contamination, the source-building separation, the crack to total area ratio, and the building ventilation rate, all of which would be expected to be site-specific. Chemical properties, including the apparent diffusion coefficient, are very important in certain cases.

**Hers and Zapf-Gilje Sensitivity Analysis.** Hers and Zapf-Gilje (2001) evaluated the MDEQ regulatory framework for a Michigan industrial consortium. They concluded that the JEM is sensitive to both the soil gas advection rate into the building and to the soil moisture content at sites with moderate to high diffusion potential, which are defined as sites where the effective diffusion coefficient for soil divided by the depth to contamination is large. For a generic approach where the depth to contamination is arbitrarily selected, the range in vapor attenuation ratio (indoor air divided by source vapor concentration) predicted by the JEM model varies over three orders of magnitude when the probable range of actual input parameters for active scenarios is considered. When good quality site-specific information is available, the uncertainty in JEM vapor

attenuation ratio is reduced to about one order of magnitude, which is reasonable for a screening level model.

Highly conservative predictions can result when actual contamination is relatively deep and there is significant bioattenuation of hydrocarbon vapors. Non-conservative predictions can result when the actual contamination is relatively shallow and there is high advection potential or preferential pathways.

It is Hers' and Zapf-Gilje's (2001) opinion that the JEM is probably not suitable for the derivation of generic criteria. They recommend a site-specific approach on a purely technical basis; however, they suggest that a reasonable compromise is a generic matrix approach that incorporates some site-specific data. A generic matrix approach that includes an initial screening step and information on depth to contamination and soil type can improve on a single criteria approach by incorporating the key factors that affect vapor intrusion and model predictions. The screening step should be used to ensure that potential high or low risk sites, where model predictions are unreliable, are appropriately addressed.

The input factor that has the greatest control on the vapor attenuation ratio is the soil type (loam) assumed for criteria development and the estimated permeability for this soil type. The input assumptions result in a low soil gas advection rate and, therefore, vapor attenuation ratio. Factors with less but still significant influence on the vapor attenuation ratio are the assumed building depressurization (1 Pasquel), building air exchange rate (1 per hour for residential and 2 per hour commercial), and building mixing height (4.88 m for residential and 2.44 m for commercial).

**Field Validation Studies.** The Panel found no unequivocal field validation of the JEM. A number of attempts have been made, however, including the three briefly described below.

#### *Chatterton Study*

Hers and Zapf-Gilje (1998a; 1998b) and Hers, in a May 4, 2000 presentation to the MESB (Harrison, 2000b), described the Chatterton (Vancouver, British Columbia) research program, which obtained vapor profile, soil gas intrusion rates and made direct measurements of indoor air in an artificially constructed environment with controlled building properties. The investigation determined soil and groundwater properties, weather, controlled the  $\Delta P$  in flux chamber experiments, and measured indoor and outdoor concentrations. Hers *et al.* (1999) were unable to fit benzene concentration profiles with the conventional JEM, and concluded that a significant degradation had to be taking place. In their work, the JEM over-predicted the gas flow rates by a factor of three to ten. They used two modified JEMs to obtain better agreement by incorporating biodegradation and advection in soil and source depletion terms. They concluded that JEM predictions are conservative by at least one to two orders of magnitude in most cases, but not in all cases. They suggested using a multilayer version of the JEM (i.e., allowing for variation of moisture content), non-aqueous phase liquid (NAPL) vapor

partitioning and biodegradation in some cases to reduce the conservative nature of the JEM, and stated the need for better information on moisture content and building properties, which, of course, are not available in the calculation of generic values. Hers advised against setting purely generic numbers for the volatilization to indoor air pathway and advocated a screening mechanism coupled with site-specific application of a modified JEM (Harrison, 2000b).

### *Massachusetts Study*

Fitzpatrick and Fitzgerald (1996) examined data from the Massachusetts Department of Environmental Protection (MDEP) for volatile organic compound contaminated sites and organized them according to soil type, depth to groundwater, distance to building and building construction. They then collected indoor air, soil gas and/or groundwater data from those sites to evaluate available transport models to describe the intrusion of vapors into buildings. They began with 6,000 files, but narrowed the potentially useful sites to 165, of which only 47 had adequate data. Of the 28 sites, which the JEM identified as exceeding the MDEP generic standards, 13 were “false positives” when the actual indoor air was examined. On the other hand, there were four cases where the indoor air was unacceptable, but the generic standards calculated using the JEM were not violated. As the details of the JEM, as well as default parameters for input are undoubtedly different for Massachusetts, these data are not directly applicable to the MDEQ approach. However, a similar study for Michigan would be useful.

### *Colorado Study*

As part of a 1997 consent order to address groundwater and indoor air contamination at one of its facilities, the Colorado Department of Transportation was ordered to prepare an Indoor Air Corrective Measures Plan to identify long-term methods for remediating indoor air. Waterstone Environmental Hydrology and Engineering, Inc. (WEHE, 2000) prepared an extensive Baseline Risk Assessment necessary to determine the site remediation goals and to provide risk estimates for exposure to air at the site. Although the Colorado Baseline Risk Assessment does not directly address the issue of JEM validation, the Panel determined that the data from that study would still be useful to the validation process. Consequently, the MDEQ was requested by the Panel to reevaluate indoor air concentrations at the Colorado Department of Transportation’s Kimberly Ann Building A site using the JEM. The MDEQ also was requested to add the Part 201 GVIIC and the MDEQ residential risk based concentrations. These latter data were added to the Colorado data to evaluate generic prediction (Table 1).

Table 1 shows that the measured trichloroethylene (TCE) indoor air concentration was greater than the MDEQ’s risk-based indoor air concentration prediction; however, the measured groundwater concentration for the chemical was less than the Part 201 GVIIC. The Part 201 GVIIC for TCE is 15,000 ppb, indicating that concentrations lower than this in groundwater are not expected to result in indoor air concentrations greater than  $14 \mu\text{g}/\text{m}^3$  at a one in 100,000 cancer risk level. However, the “Log-Normal Mean

**Table 1. Evaluation of Michigan's Part 201 Groundwater Volatilization to Indoor Air Inhalation Criteria and Residential Risk Based Concentrations using the Estimated Indoor Air Concentrations for the Colorado Department of Transportation's Kimberly Ann Building A Site and the Johnson-Ettenger Model. <sup>(1)</sup>**

Contaminant	Estimated Kimberly Ann A Groundwater Concentration $\mu\text{g/L}$ (2)	Michigan Part 201 Residential Groundwater Volatilization to Indoor Air Inhalation Criteria $\mu\text{ g/L}$	Estimated Mean Kimberly Ann A Indoor Air Concentration $\mu\text{g/m}^3$ (3)	Log-Normal Mean Measured Kimberly Ann A Indoor Air Concentration $\mu\text{g/m}^3$	Maximum Measured Kimberly Ann A Indoor Air Concentration $\mu\text{g/m}^3$	Mean Background Concentration $\mu\text{g/m}^3$	Risk Based Indoor Air Concentration ( $1 \times 10^{-6}$ risk level or HQ=1) $\mu\text{g/m}^3$	Michigan Risk Based Indoor Air Concentration ( $1 \times 10^{-5}$ risk level or HQ=1) $\mu\text{ g/m}^3$
1,1,1-TCA	2382	660,000	9.8 - 31	47.9	140	1.89	445	1,000
1,1,2-TCA	24.3	17,000	0.005 - 0.034	< 1.1	< 1.1	< 0.1	0.14	1.5
1,1-DCA	183	1,000,000	0.22 - 1.1	4.1	6.7	< 0.08	224	520
1,1-DCE	4852	200	32 - 94	32.9	93	0.022	0.046	0.49
1,2,4-Trimethylbenzene	3	56,000 <sup>(b)</sup>	0.0024 - 0.013	1.7	4.2	3.7	2.66	1,300
1,2-DCA	10.8	9,600	0.0036 - 0.025	0.08	0.13	0.067	0.09	0.94
Benzene	20	5,600	0.023 - 0.12	3.9	14	4.7	0.28	2.9
Chloroform	7.9	28,000	0.0066 - 0.039	1.6	6.3	2.4	0.1	10
cis-1,2-DCE	4.6	96,000	0.0076 - 0.037	< 0.79	< 0.79	< 0.79	37	37
DCM	422	N/C <sup>(c)</sup>	0.27 - 1.7	1.9	2.8	2.33	4.9	N/C <sup>(c)</sup>
Ethylbenzene	3.2	170,000 <sup>(b)</sup>	0.0039 - 0.019	1.7	5.2	2.5	450	1,000
TCE	1390	15,000	3.0 - 13	21.3	81	0.33	1.33	14
Toluene	3.4	530,000 <sup>(b)</sup>	0.0040 - 0.033	13.3	34	21.6	178	420
Vinyl Chloride	1 <sup>(a)</sup>	110	0.017 - 0.033	0.012	0.07	0.011	0.03	0.29
Xylenes (m&p)	3.9	190,000 <sup>(b)</sup>	0.0036 - 0.019	5.5	16	8.6	315	4,600

(1) From WEHE, 2000 as modified by Crum, 2000.

(2) Estimated (Kriged) groundwater chemical concentration below Kimberly Ann Building A.

(3) Indoor Air Concentration estimated using the Johnson-Ettenger Model, calibrated using kriged groundwater concentrations and measured indoor air concentrations of 1,1-DCE at Kimberly Ann A. The lower values are based on the mean and the upper values are based on the maximum measured 1,1-DCE concentration.

(a) Vinyl Chloride was not detected in any well and, therefore, could not be kriged; value is one-half the minimum detection limit.

(b) Criteria is greater than water solubility and, therefore, defaults to water solubility.

(c) Currently, there are no MDEQ indoor air criteria developed for this chemical.

Measured Kimberly Ann Building A Indoor Air Concentration” is  $21.3 \mu\text{g}/\text{m}^3$ , slightly greater than  $14 \mu\text{g}/\text{m}^3$ . This measured indoor air concentration is associated with a TCE groundwater concentration (1,390 ppb), an order of magnitude lower than the Part 201 GVIIC (15,000 ppb). An example of a situation where a groundwater concentration greater than the Part 201 GVIIC is present and the indoor air concentration is above the risk-based indoor air concentration is 1,1-dichloroethene. In this case, the Part 201 GVIIC served as a fairly accurate predictive indication that unacceptable indoor air concentrations may occur from groundwater concentrations greater than the GVIIC (Crum, 2000).

The benzene data are more difficult to interpret due to the background air concentrations. The benzene mean indoor air concentration is greater than the MDEQ’s risk-based indoor air concentration and the groundwater concentration is less than the Part 201 GVIIC; however, the mean measured indoor air concentration is less than the measured background concentration. As a result, it cannot be concluded that benzene indoor air concentrations were caused from groundwater volatilization of benzene into the indoor air (Crum, 2000).

While Colorado soils are different than Michigan’s, this analysis provides one of the few comparison points for the JEM model.

### **Toxicological Considerations**

The SVIIC and GVIIC are intended to represent concentrations that are protective of adverse human health effects from inhalation of contaminant vapors migrating from soil and groundwater into residential or commercial/industrial buildings. The migration of contaminant vapors from soil and groundwater is estimated using the JEM. The use of this model and the generic input parameter values that were selected has been evaluated as previously described in this report.

An acceptable contaminant concentration in soil or groundwater (SVIIC or GVIIC) that would not be expected to produce a harmful level in indoor air can be estimated by incorporating generic input values into the JEM for parameters related to the subsurface and building characteristics and chemical-physical constants pertaining to the contaminant in question. Calculation of these criteria requires the use of generic human exposure values that represent the time that an individual may be inhaling a chemical in a residential or commercial/industrial building. In addition, chemical-specific toxicity values are required such as the inhalation unit risk factor (IURF) and reference concentration (RfC) for carcinogenic and non-carcinogenic chemicals, respectively. The majority of inhalation toxicity values are obtained from the USEPA Integrated Risk Information System (IRIS) database, while others are developed by the MDEQ. All inhalation toxicity values used in the calculation of the Part 201 SVIIC and GVIIC are made available by the MDEQ (2000).

The generic exposure assumptions and chemical-specific toxicity values used to develop SVIIC and GVIIC were examined to determine whether they have been

selected to result in criteria that are sufficiently protective of public health. The IURFs for carcinogenic chemicals are derived using the 95 percent upper bound value on the calculated risk of one additional cancer above the background cancer rate per 100,000 individuals (Section 20a(4), Part 201). For noncarcinogenic chemicals, the RfC is used assuming a hazard quotient of one, which allows a daily exposure to a contaminant at a concentration equal to the RfC. These toxicity values for carcinogenic and toxic, noncarcinogenic chemicals are considered to possess a high level of safety (i.e., they are conservative in their protection of public health), because the approaches used to derive the values are structured to err on the side of public health protection (Gracki *et al.*, 2000).

The generic exposure assumptions selected by the MDEQ to calculate soil and groundwater criteria protective of indoor air appear to be realistic. Inhalation exposure in a residential setting was assumed to occur for 350 days/year, and 245 days/year for commercial/industrial settings. The duration of these exposures is presumed to be 30 years and 21 years, respectively, for residential and commercial/industrial settings. Because continuous exposure to carcinogens is not representative of worker exposures in commercial/industrial settings, an adjusted intake rate (AIR) of 20 m<sup>3</sup>/day divided by 10 m<sup>3</sup>/day (i.e., AIR = 2) was added to the criteria calculation (i.e., the volume of air breathed by an adult in a residential setting is 20 m<sup>3</sup>/day compared to 10 m<sup>3</sup>/day for an adult worker in a commercial/industrial setting). This is reportedly consistent with the USEPA (1997a) and OSHA (1988) standard default values (MDEQ,1998).

The Panel believes that these and other values used in the calculation of the SVIIC and GVIIC are conservative and result in protection of public health. However, no apparent consideration was given to the fact that the inhalation rate of infants and children is higher than adults, which leads to higher exposures in these presumably more susceptible individuals. Exposures to children would occur in residential settings and attention should have been given to this possibility. Thus, it must be assumed that the criteria values developed using the generic procedure are relatively less protective for infants and children than for adults. Whether the values protective of adults are sufficiently protective of infants and children will likely be a subject of debate. Use of the inhalation rate for children in a residential setting would have reflected a more prudent choice for calculation of criteria values.

Finally, the MDEQ (1998) TSD indicates that the only exposure consideration given was inhalation of an indoor air contaminant volatilizing into a building from contaminated soil and/or groundwater. Thus, human intake through other exposure scenarios, such as those occurring with indoor uses of groundwater (e.g., showering and cooking), were not considered. Nor were the risks from hazards arising from airborne chemicals, such as flammability and corrosion, taken into account. These possibilities should be considered to determine whether they are insignificant relative to health risks resulting from subsurface vapor migration to indoor air.

In summary, the application of inhalation exposure and chemical toxicity values in calculating criteria to detect potentially unsafe levels of contaminants in the soil and



groundwater that can volatilize and enter the indoor air of residential or commercial buildings represents a scientifically defensible process. The estimated exposure and toxicity values utilized in the estimation of levels of specific contaminants in the subsurface capable of entering buildings would appear to be realistic and conservative of public health. Their use in combination with generic modeling results using the Johnson - Ettinger (1991) method would yield calculated criteria that are likely to be protective of public health, particularly for adults. However, because the possibility of indoor air exposure to infants and children was apparently not taken into consideration, it is presumed that the margin of safety for this portion of the population may be less than for adults.

## **Findings and Conclusions**

The specific charge given to the MESB by Governor John Engler was to evaluate the MDEQ's approach to evaluating indoor inhalation exposure pathway risks at sites of environmental contamination and to determine whether it provides a scientifically and technically defensible strategy for the development of generic cleanup criteria for this exposure pathway (Engler, 1999).

Situations in which the volatilization of contaminants in soil or groundwater to indoor air is the controlling exposure pathway are rare. Generic criteria developed for chemical contaminants using this pathway of human exposure must be based upon accurate science with carefully selected physical, chemical, and transport properties, and must be extensively field tested to ensure that they are protective of public health on the one hand, but avoid a preponderance of false positives on the other. The Panel concludes that the choice of the JEM (Johnson and Ettinger, 1991) as the model for the calculation of such generic criteria in the MDEQ (1998) TSD is appropriate. The model is consistent with its intended generic use; its foundation is based in sound science; and it is widely accepted by other regulatory agencies including the USEPA. It is recommended by the ASTM (1995) to guide corrective actions at petroleum release sites, and it is computationally and parametrically straightforward to use. In addition, the calculational simplicity and excellent documentation in the choice of the JEM allow ease of site-specific modification of the generic criteria should a property owner desire to adapt the generic criteria to better represent actual facility conditions. There are currently no competing models in common use that are not derived from the JEM.

Because it models a complex problem, the JEM requires an unusually large number of input parameters. The values of some of these parameters may vary over a wide range, resulting in widely varying output predictions (Hers, 2000; USEPA, 1996). Thus, the use of field-derived data and data from more controlled studies is required to: (1) demonstrate the applicability and validity of the JEM for the prediction of site-specific conditions and (2) confirm the selection of generic input parameters. The Panel concludes that neither under field nor more controlled conditions has a thorough validation of the model been obtained. Consequently, it would be useful for both the USEPA and the MDEQ to orient their extensive data collection at relevant sites to providing data that can be used for validation of the model and generic input parameters

used in Michigan. As presented in this report, the MDEQ JEM can be used to generate indoor air contaminant concentrations to correlate with actual data.

Although slightly different, the input parameters chosen by the USEPA and the MDEQ for use with the JEM appear to be defensible to produce generic criteria that would be protective of public health and that would identify only those contaminant site situations that may require deed restrictions, engineering controls, further site cleanup, or a combination of remedial techniques. However, the Panel remains concerned that sufficient data are not available at this time to fully assess whether the input parameter values selected by the MDEQ for use in the JEM are appropriate choices for the development of generic criteria. The data generated from the Chatterton, Massachusetts, Colorado, and MDEQ studies, while important to this evaluation, are currently too limited for the Panel to reach a definitive conclusion. Despite the above, the Panel reaffirms the JEM as the method of choice for evaluating indoor inhalation exposure pathway risks and advises the continued effort to obtain sound scientific field validation to guide the application of the algorithm.

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## **Appendix 1.**

### **Part 201 Generic Groundwater and Soil Volatilization to Indoor Air Inhalation Criteria Technical Support Document**

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**PART 201  
GENERIC GROUNDWATER AND SOIL VOLATILIZATION  
TO INDOOR AIR INHALATION CRITERIA:  
TECHNICAL SUPPORT DOCUMENT**

**Michigan Department of Environmental Quality  
Environmental Response Division**

**August 31, 1998**

This memorandum describes the technical development of generic groundwater and soil volatilization to indoor air inhalation criteria (GVIIC and SVIIC, respectively) for residential and commercial/industrial land use categories. The generic GVIIC and SVIIC are presented in Operational Memorandum #18: Part 201 Generic Cleanup Criteria Tables.

These criteria are provided pursuant to Sections 20120a(1)(a), (b), (d), and 20120a(3) of Part 201, Environmental Remediation, of the Natural Resources and Environmental Protection Act, 1994 PA 451, as amended. Section 20120a(3) requires the department to develop criteria using generic health risk assessment assumptions that appropriately characterize human exposures associated with land uses, and to use reasonable and relevant exposure pathways in developing these criteria. The migration of contaminant vapors (i.e., in the gas or vapor phase) from groundwater and soil into buildings or other enclosed spaces, thereby exposing occupants in the building, is a relevant human exposure pathway that must be considered for all generic and certain limited land use closures.

GVIIC and SVIIC may be the controlling criteria at some facilities depending on the groundwater and soil characteristics, land use, and contaminants present. Therefore, generic scenarios were developed to generate GVIIC and SVIIC for use as a screening tool to identify sites that warrant further consideration of the indoor air inhalation pathway. In practice, these criteria serve as a reference point for interpreting the significance of potential health risks associated with the indoor air inhalation pathway. As such, these values can be used for determining whether a property is a facility, and are relevant in determining the adequacy of a remedial action plan (RAP). Application of the generic GVIIC and SVIIC is intended to accelerate remedial decision-making, and facilitate the preparation, development, and completion of RAPs. Guidance on the application and implementation of these criteria is presented in the latter part of this document.

The Part 201 generic GVIIC and SVIIC are considered to be protective of only those health effects that may result from chronic inhalation exposure to hazardous substances. They do not represent levels that are protective of aesthetic characteristics such as odors, and are not protective of effects that may result from human intake or contact through other exposure pathways than inhalation. Inhalation exposures resulting from indoor uses of groundwater such as showering, laundry, and cooking are also not considered. Additionally, these criteria may not be protective of physical hazards, such as flammability/explosivity, reactivity, corrosivity, and also ecological impacts. An evaluation of the relevance of other exposure pathways and short-term effects must be conducted to determine if more restrictive criteria are necessary for protecting these endpoints.

**BACKGROUND AND CONCEPTUAL SITE MODEL**

Much of the scientific research evaluating the migration of contaminant vapors into buildings has stemmed from efforts to address human health risks associated with the intrusion and accumulation of radon vapors. The mechanisms and factors involved in the transport of soil contaminant gases (vapors), primarily of volatile organic compounds (VOCs) into buildings, are similar to those of radon. A review of the scientific literature on this issue indicates that soil-gas entry into buildings is the result of both diffusive and convective transport processes, and that site-specific physical characteristics will determine the significance of each.

The Johnson and Ettinger (1991) Model (JEM) was selected as the best available quantitative method for development of Part 201 generic GVIIC and SVIIC. Johnson and Ettinger developed a mathematical model to estimate diffusive and convective transport of contaminant vapors emanating from soil into indoor spaces. Because the JEM only describes contaminant vapor migration in soil, the migration of contaminants from groundwater (i.e., diffusion in a liquid phase instead of a vapor phase) was characterized using a methodology similar to that presented in the American Society for Testing and Materials (ASTM, 1995) for development of the generic GVIIC. The JEM is also described in EPA's guidance document for Assessing Potential Indoor Air Impacts at Superfund Sites (EPA, 1992a) and EPA's Soil Screening Guidance: Technical Background Document (EPA, 1996a), and is used by ASTM to guide risk-based corrective actions (RBCA) at petroleum release sites (ASTM, 1995).

The JEM was chosen because it is a relatively simple mathematical computation for development of generic screening criteria, yet effectively represents the physical and chemical processes that influence the behavior of contaminant vapors in soil. Predictions from the JEM agree closely with those of a more sophisticated three-dimensional numerical model developed to predict the transport and intrusion of radon into buildings (Loureiro et al., 1990). Johnson and Ettinger (1991) also note that the results of the JEM were in qualitative agreement with published experimental case studies. The JEM is widely used by EPA, ASTM, and several other states for screening contaminated sites for this pathway. Lastly, the JEM was selected because simple site-specific measurements may be obtained and incorporated into the equations to derive site-specific criteria.

The modeling of contaminant transport through soil and into buildings is a complex process. As contaminants move from the source to soil vapor to building vapor, a number of factors influence the amount of contamination that migrates from one location to the next. These factors are accounted for in the equilibrium partitioning calculations and the model attenuation coefficient. Overall, the JEM consists of five fundamental steps.

#### Step 1: Calculation of the Ratio of the Soil Vapor Phase Concentration to Total Concentration at the Source

This step estimates a concentration ratio,  $CR_{source}$ , which relates the vapor phase concentration of contaminant in the soil pore air spaces to the “total” concentration present in the soil or groundwater. The total concentration of a chemical in soil is equal to the amount present in three phases: 1) vapor in pore air, 2) dissolved in pore water, and 3) sorbed to soil particles. In soil, this ratio is calculated considering the interaction of the physicochemical properties of the chemical with physical properties of the soil, referred to as phase partitioning. For groundwater, the ratio is determined assuming that the vapor phase concentration in the overlying soil is in equilibrium with the aqueous phase concentration as a function of the Henry’s Law Constant.

#### Step 2: Calculation of the Effective Diffusion Coefficient

This step involves determination of the chemical-specific effective diffusion coefficient ( $D^{eff}$ ) in soil or groundwater. Diffusion represents the rate of contaminant flow through soil and/or groundwater, which occurs through both pore air and pore water spaces. In general, the  $D^{eff}$  accounts for chemical-specific and medium-specific characteristics that act to reduce contaminant flow, a process collectively known as tortuosity. The partitioning behavior of contaminants between phases (liquid, solid, and gas) as they flow through interconnected pore spaces also influence contaminant diffusion.

Calculation of the  $D^{eff}$  for groundwater is more involved than for soil in that diffusion of the contaminant through the capillary fringe to the overlying soil must be considered. The capillary fringe is a predominantly water saturated zone located between the groundwater table and the unsaturated zone. An approach similar to that presented in ASTM (1995) RBCA was used. This is required since the JEM is designed to predict transport of contaminant vapors only through soil. Therefore, diffusion of predominantly water-borne contaminants through the capillary fringe is modeled to yield the soil vapor phase levels required for input into the JEM.

#### Step 3: Calculation of the Infiltration Rate of Contaminant Vapors into the Building

Next, the emission or infiltration rate of vapors through cracks in the concrete floor/walls is estimated. This value is first dependent on the amount of contaminant transported via diffusion from the source to the building. The infiltration rate of vapors into the building is then a function of the total crack area, building pressurization relative to the surrounding soil, and the soil vapor permeability in the ‘zone of influence.’ The zone of influence represents the distance from the building shell (below grade) to a point in the soil where convective forces are no longer acting to sweep contaminant vapors toward cracks in the subgrade portion of the building. The magnitude of the indoor-outdoor pressure differential, area of the cracks, and soil vapor permeability will collectively determine the extent of the zone of influence, hence the vapor intrusion rate into the building.

#### Step 4: Calculation of the Building Vapor Concentration to Total Soil or Groundwater Vapor Source Concentration Ratio

This step estimates another concentration ratio,  $CR_{building}$ , which relates the indoor vapor concentration in the building to the vapor phase concentration at the source, determined in step 1 above. The factors that influence this ratio are the factors associated with steps 2 and 3 above, and the building volume and indoor air ventilation rate.

#### Step 5: Back-calculation of the GVIIC and/or SVIIC

An acceptable total concentration in soil (ug/kg) or groundwater (ug/l) is determined in this step. Given the acceptable indoor air concentration that may be inhaled daily by a human without adverse health effects, and the building vapor concentration generated per unit soil or groundwater concentration (i.e.,  $CR_{building}$ ) the corresponding

GVIIC or SVIIC is calculated. The acceptable indoor air concentration is based on the generic land-use specific exposure assumptions and the toxicity characteristics of the contaminant.

The JEM may be used to solve both steady state (i.e., infinite source) and quasi-steady state (i.e., finite source) conditions for contaminants in soil. Finite source modeling is not feasible for generic modeling of groundwater contaminant volatilization to indoor air since the location, medium and volume of source cannot be standardized. Therefore, only a methodology for calculating finite source-based SVIIC is provided.

The generic conceptual site models (CSM) used to develop the generic residential and commercial/industrial GVIIC and SVIIC are illustrated in Figure 1 and 1a. Some of the physical attributes that were considered characteristic of the residential and commercial/industrial land use categories are shown, as well as the key parameters of the JEM used to calculate the generic criteria.

### **Residential Land Use Scenario**

A single family detached home is the predominant residential housing type (EPA, 1996b). Information contained in a report entitled *Characteristics of New Housing: 1995* (U.S. DOC and U.S. HUD, 1996) was reviewed to determine a representative generic residential home size and construction type for houses in Michigan. This review found that 90 percent of homes built in the Midwest between 1975 and 1995 have basements or crawl spaces. Therefore, a single story house (ranch) with a basement was assumed for generic calculations. The size of single family residences in the Midwest has increased steadily from an average low of 1,645 ft<sup>2</sup> (floorspace area) in 1975 to an average high of 2,095 ft<sup>2</sup> in 1995. House size is a sensitive input into the JEM as it influences the potential total crack area available for vapor infiltration and the total volume of air for contaminant mixing and ventilation. A frequency distribution of the floorspace range for residential homes built in 1995 is provided in the table below.

Size	Percentage of Homes
Under 1,200 ft <sup>2</sup>	11%
1,200 to 1,599 ft <sup>2</sup>	23%
1,600 to 1,999 ft <sup>2</sup>	23%
2,000 to 2,399 ft <sup>2</sup>	18%
2,400 to 2,999 ft <sup>2</sup>	14%
Greater than 3,000 ft <sup>2</sup>	11%

Based on this range, 1,200 ft<sup>2</sup> (111.5 m<sup>2</sup>) was selected as an upper percentile estimate (approximately 90th percentile) of the floorspace area for generic residential calculations. Applying two eight-foot ceilings yields a total indoor air volume of 19,200 ft<sup>3</sup>, or 544 m<sup>3</sup>.

For the generic residential scenario, the soil contaminant source is assumed to lie directly below the foundation floor, while contaminants in groundwater are assumed to be present 100 centimeters below the foundation floor.

### **Commercial/Industrial Land Use Scenario**

The commercial and industrial land use categories were grouped together since the operations at the majority of industrial land uses involve separate spaces/rooms that typically adjoin, or are located next to the main industrial building(s). These spaces or buildings are generally similar in size, type, and ventilation to many other commercial structures. Therefore, the generic SVIIC and GVIIC for commercial and industrial land use categories were consolidated into one set of criteria that reflect a common receptor population to both land use types, and that will assure protection of that portion of the population that would likely experience the greatest amount of contaminant exposure.

Choice of the generic commercial building size (floorspace area) and type was guided by a report entitled *Commercial Buildings Characteristics 1992* which documents the results of a Commercial Buildings Energy Consumption Survey (CBECS) conducted by the United States Department of Energy (DOE, 1994). This survey is completed on a triennial basis and provides a wide range of statistics related to physical commercial building characteristics on a national and regional scale. Building size and other variables measured in the survey are estimates based on reported data from a randomly chosen subset of the entire population of commercial buildings. Data from nearly 6,600 buildings nationwide were obtained.

Commercial building activities/operations span a wide range, however, the majority of buildings are generally similar in size. As shown in the table below, over 50 percent of the commercial buildings have a floor area between 1,000 and 5,000 ft<sup>2</sup>, with the remaining percentage of buildings greater than 5,000 ft<sup>2</sup>.

Building Floorspace (ft <sup>2</sup> )	Number of Buildings East North Central U.S. (Includes Michigan)
1,001 to 5,000	422
5,001 to 10,000	149
10,001 to 25,000	104
25,001 to 50,000	37
50,001 to 100,000	22
100,001 to 200,000	9
200,001 to 500,000	5
Over 500,000	1
Total:	749

In addition, the CBECS survey reports that 381 of the 749 buildings are single floor construction types. The three most common commercial building activities, listed in order of most frequent occurrence, are categorized as 'Mercantile and Service,' 'Warehouse and Storage,' and 'Office.' The floorspace areas for these building categories were not provided by region. However, the nationwide reported **median** floorspace areas for the three categories are 4,000, 5,000, and 5,000 ft<sup>2</sup>, respectively. The median statistic instead of the mean is the most appropriate measure of central tendency in this instance as the distribution for this variable is skewed toward commercial building sizes at the low end of the range (i.e., 1000 to 5000 ft<sup>2</sup>, see table above).

The nationwide median and mean floorspace area for a number of other building activities are shown below.

The 'Mercantile and Service' category includes buildings such as gasoline service stations, automobile dealers, department stores, furniture stores, multi-retail establishments, laundry and dry cleaners, post offices, and shopping malls. This category was selected to represent the generic building size and floorspace area for development of commercial/industrial SVIIC and GVIIC. Only 'Food Sales' and 'Food Service' buildings have lower median values. Therefore, 4,000 ft<sup>2</sup> (372 m<sup>2</sup>) is the commercial/industrial building size default floorspace area. The total indoor air volume, considering one floor with an eight foot ceiling, is 908 m<sup>3</sup>.

Building Activity	Number of Buildings	Mean ft <sup>2</sup> (thousand)	Median ft <sup>2</sup> (thousand)
Education	301	28.2	9.0
Food Sales	130	5.8	2.6
Food Service	260	5.7	3.4
Health Care	63	27.9	4.3
Lodging	154	18.8	8.0
<b>Mercantile and Service</b>	<b>1,272</b>	<b>9.7</b>	<b>4.0</b>
Office	749	16.4	5.0
Public Assembly	278	16.4	5.9
Public Order and Safety	60	13.7	5.0
Religious Worship	366	10.2	4.4
Warehouse and Storage	761	15.1	5.0
Other	69	16.4	4.0
Vacant	319	13.8	4.2

The soil contaminant source is considered to be located directly below the foundation floor, and groundwater is assumed to be present 3 meters (300 cm) below grade.

Other attributes of the generic scenarios are identified and explained in the following sections.

#### **JEM Assumptions**

There are a number of assumptions underlying the JEM. These characteristics are assumed to apply in the calculation of the SVIIC and GVIIC and do not need to be confirmed on a site-specific basis.

- The contaminant is homogeneously distributed within the soil or groundwater source.
- Soil is homogeneous such that the effective diffusion coefficient is constant.
- Contaminant loss from leaching downward does not occur.
- Source degradation and transformation is not considered.
- Contaminant concentration at the interface between the soil particle surface and soil pore air space is zero (i.e., boundary layer resistance is zero).
- Convective vapor flow near the building foundation is uniform.

- Convective vapor flow rates decrease with increasing distance between the contaminant source and the building.
- Contaminant vapors enter the building through openings in the walls and foundation at or below grade.
- Both the building ventilation rate and the difference in pressure between the building interior and the surrounding soil are constant.
- All contaminant vapors directly below the building will enter the building, unless the floor and walls are perfect vapor barriers.
- The building contains no other contaminant sources or sinks, and contaminant vapor dispersion is instantaneous and homogeneous.

## TECHNICAL DEVELOPMENT AND GENERIC EQUATIONS

Equations 1 through 4 are used to calculate chemical-specific SVIIC and GVIIC for carcinogenic and noncarcinogenic contaminants. Chemical-specific **soil** concentrations protective of unacceptable indoor air inhalation risks are calculated as follows:

### Carcinogens

$$SVIIC = \frac{TR \times AT \times AIR}{IURF \times EF \times ED \times CR_{building}} \quad (1)$$

where,

<i>SVIIC</i>	(Soil Volatilization Indoor Air Inhalation Criteria)	= chemical-specific, ug/kg
<i>TR</i>	(Target risk)	= 1E-5
<i>AT</i>	(Averaging time)	= 25,550 days (70 x 365)
<i>AIR</i>	(Adjusted inhalation rate)	= 1 (Residential; [(20m <sup>3</sup> /day)/(20m <sup>3</sup> /day)]) = 2 (Commercial/Industrial; [(20m <sup>3</sup> /day)/(10m <sup>3</sup> /day)])
<i>IURF</i>	(Inhalation unit risk factor)	= chemical-specific, (ug/m <sup>3</sup> ) <sup>-1</sup>
<i>EF</i>	(Exposure frequency)	= 350 days/year (Residential) = 245 days/year (Commercial/Industrial)
<i>ED</i>	(Exposure duration)	= 30 years (Residential) = 21 years (Commercial/Industrial)
<i>CR<sub>building</sub></i>	(Ratio of indoor vapor concentration to soil or groundwater vapor source concentration)	= chemical-specific, (ug/m <sup>3</sup> )/(ug/kg)*

### Noncarcinogens

$$SVIIC = \frac{THQ \times AT}{(1/RfC) \times EF \times ED \times CR_{building}} \quad (2)$$

where,

<i>SVIIC</i>	(Soil Volatilization Indoor Air Inhalation Criteria)	= chemical-specific, ug/kg
<i>THQ</i>	(Target hazard quotient)	= 1
<i>AT</i>	(Averaging time)	= 10,950 days (Residential) = 7,665 days (Commercial/Industrial)
<i>EF</i>	(Exposure frequency)	= 350 days/year (Residential) = 245 days/year (Commercial/Industrial)
<i>ED</i>	(Exposure duration)	= 30 years (Residential) = 21 years (Commercial/Industrial)

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\* *CR<sub>building</sub>* is expressed as a concentration ratio which relates the indoor air vapor concentration (ug/m<sup>3</sup>) to the vapor-phase concentration in the soil, *CR<sub>soil</sub><sup>soil</sup>*, or groundwater, *CR<sub>source</sub><sup>gw</sup>*, source. *CR<sub>source</sub><sup>soil</sup>* and *CR<sub>source</sub><sup>gw</sup>* are also concentration ratios and are defined below.

$RfC$	(Reference concentration)	= chemical-specific, $\text{ug}/\text{m}^3$
$CR_{building}$	(Ratio of indoor vapor concentration to soil or groundwater vapor source concentration)	= chemical-specific, $(\text{ug}/\text{m}^3)/(\text{ug}/\text{kg})^*$

Chemical-specific **groundwater** concentrations protective of unacceptable indoor air inhalation risks are:

#### Carcinogens

$$GVIIC = \frac{TR \times AT \times AIR}{IURF \times EF \times ED \times CR_{building}} \quad (3)$$

where,

$GVIIC$	(Groundwater Volatilization Indoor Air Inhalation Criteria)	= chemical-specific, $\text{ug}/\text{l}$
$TR$	(Target risk)	= $1\text{E}-5$
$AT$	(Averaging time)	= 25,550 days ( $70 \times 365$ )
$AIR$	(Adjusted inhalation rate)	= 1 (Residential; $[(20\text{m}^3/\text{day})/(20\text{m}^3/\text{day})]$ ) = 2 (Commercial/Industrial; $[(20\text{m}^3/\text{day})/(10\text{m}^3/\text{day})]$ )
$IURF$	(Inhalation unit risk factor)	= chemical-specific, $(\text{ug}/\text{m}^3)^{-1}$
$EF$	(Exposure frequency)	= 350 days/year (Residential) = 245 days/year (Commercial/Industrial)
$ED$	(Exposure duration)	= 30 years (Residential) = 21 years (Commercial/Industrial)
$CR_{building}$	(Ratio of indoor vapor concentration to soil or groundwater vapor source concentration)	= chemical-specific, $(\text{ug}/\text{m}^3)/(\text{ug}/\text{l})$

#### Noncarcinogens

$$GVIIC = \frac{THQ \times AT}{(1/RfC) \times EF \times ED \times CR_{building}} \quad (4)$$

where,

$GVIIC$	(Groundwater Volatilization Indoor Air Inhalation Criteria)	= chemical-specific, $\text{ug}/\text{l}$
$THQ$	(Target hazard quotient)	= 1
$AT$	(Averaging time)	= 10,950 days (Residential) = 7,665 days (Commercial/Industrial)
$EF$	(Exposure frequency)	= 350 days/year (Residential) = 245 days/year (Commercial/Industrial)
$ED$	(Exposure duration)	= 30 years (Residential) = 21 years (Commercial/Industrial)
$RfC$	(Reference concentration)	= chemical-specific, $\text{ug}/\text{m}^3$

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\*  $CR_{building}$  is expressed as a concentration ratio which relates the indoor air vapor concentration ( $\text{ug}/\text{m}^3$ ) to the vapor-phase

concentration in the soil,  $CR_{source}^{soil}$ , or groundwater,  $CR_{source}^{gw}$ , source.  $CR_{source}^{soil}$  and  $CR_{source}^{gw}$  are also concentration ratios and are defined below.

$CR_{building}$	(Ratio of indoor vapor concentration to soil or groundwater vapor source concentration)	= chemical-specific, $(\text{ug}/\text{m}^3)/(\text{ug}/\text{l})^*$
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### **Toxicity Values and Exposure Assumptions**

Note that the reference concentrations (RfC) and inhalation unit risk factor (IURF) toxicity values are presented as concentrations in air (ug/m<sup>3</sup>). A default body weight of 70 kg and an inhalation rate of 20 m<sup>3</sup>/day are accounted for in the development of the inhalation toxicity values. As a result, they are not included in the generic equations. In addition, these values are set to be protective against continuous, 24 hour/day exposure. Because continuous exposure is not characteristic of worker exposures in commercial and industrial settings, an adjustment is necessary to account for the volume of air breathed only while in the workplace. Therefore, an adjusted inhalation rate (AIR) of 20 m<sup>3</sup>/day /10 m<sup>3</sup>/day (i.e., a factor of 2) was added to the commercial/industrial GVIIC and SVIIC equations. The AIR is applied only to carcinogenic chemicals for consistency with currently proposed Air Quality Division administrative rules. The 10 m<sup>3</sup>/day intake rate for workers is consistent with both EPA and Occupational Safety and Health Administration (OSHA) standard default values and assumes that a worker engaged in moderate activity will respire more heavily while on the job than during light activity and resting portions of a day.

The default values for EF and ED are the same as those used in the Part 201 algorithms for calculating the health-based drinking water values, since the same receptor population (i.e., resident or worker) is also present in a building for the same time period breathing indoor air.

### **Building Indoor Air Vapor Concentration to Groundwater or Soil Vapor Concentration Ratio**

The ratio of the indoor vapor concentration to the source vapor concentration is calculated as the product of the vapor phase concentration at the source to the total source concentration ratio and the attenuation coefficient:

$$CR_{building} = CR_{source}^{soil/gw} \times \alpha \quad (5)$$

where,

$CR_{building}$	(Ratio of indoor vapor concentration to soil or groundwater vapor source concentration)	= chemical-specific, units noted above for groundwater and soil
$\alpha$	(Attenuation coefficient)	= chemical-specific, unit less
$CR_{source}^{soil/gw}$	(Ratio of vapor phase concentration to total soil or groundwater source concentration)	= chemical-specific, units given below

### **Vapor-phase Concentration to Total Source Concentration Ratio**

The ratio of the “vapor-phase” contaminant concentration to the “total” concentration at the source for soil ( $CR_{source}^{soil}$ ) is calculated differently than for groundwater ( $CR_{source}^{gw}$ ), since equilibrium conditions for a given contaminant are reached differently in soil than in water. Under equilibrium conditions in soil, contaminant concentrations in the vapor, soil moisture (i.e., water), and sorbed phases are assumed to be in constant proportions to each other and to the total contaminant concentration (i.e., at steady state). This is a conservative assumption as constant and continuous equilibrium between phases is unlikely to occur. This is because the standard temperature and pressure conditions under which the equilibrium constants are developed do not remain constant in the environment. For these calculations it is also assumed that no residual contaminant is present in the soil pores as free liquid or precipitate (solid). The ratio of the vapor phase concentration to the unit source contaminant concentration (i.e., 1 ug/kg) for soil is written as:

$$CR_{source}^{soil} = \frac{H' \times TAF \times C_s \times \rho_b \times 10^{-3} \text{ kg / g} \times 10^6 \text{ cm}^3 / \text{m}^3}{\theta_w + (k_d \times \rho_b) + (H' \times TAF \times \theta_a)} \quad (6)$$

where,

$CR_{source}^{soil}$	(Ratio of vapor phase concentration to total soil source concentration)	= chemical-specific, (ug/m <sup>3</sup> )/(ug/kg)*
$H'$	(Dimensionless Henry's law constant, where $H' = HLC \times 41$ )	= chemical-specific, unit less

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\*  $CR_{source}^{soil}$  is expressed as a concentration ratio relating the vapor-phase contaminant concentration generated per unit contaminant concentration in soil (ug/kg).

<i>HLC</i>	(Henry's Law Constant)	= atm·m <sup>3</sup> /mol, chemical-specific
<i>TAF</i>	(Temperature adjustment factor)	= 0.5 (HLC adjusted to Michigan annual average soil temperature of 10° Celsius)
<i>C<sub>s</sub></i>	(Uniform concentration in soil)	= 1 ug/kg
<i>ρ<sub>b</sub></i>	(Dry soil bulk density)	= 1.5 g/cm <sup>3</sup> (EPA, 1996a)
<i>θ<sub>w</sub></i>	(Soil water-filled porosity)	= 0.3 cm <sup>3</sup> /cm <sup>3</sup> (EPA, 1996a)
<i>k<sub>d</sub></i>	(Soil-water partition coefficient)	= chemical-specific, cm <sup>3</sup> /g (equivalent to L/kg)
	Organic compounds	= K <sub>oc</sub> (chemical-specific, cm <sup>3</sup> /g) x f <sub>oc</sub> (0.002)
<i>θ<sub>a</sub></i>	(Soil air-filled porosity)	= 0.13 cm <sup>3</sup> /cm <sup>3</sup> (EPA, 1996a)

This ratio is developed considering the partitioning characteristics of the chemical in conjunction with the soil properties, such as the organic carbon content of the soil (*f<sub>oc</sub>*). For purposes of back-calculation, a uniform unit (1 ug/kg) concentration in soil is assumed.

Consistent with the development of soil-water partitioning criteria (MDEQ, 1998a), soil property default values representative of a loam soil type and subsurface conditions were used as provided by EPA (1996a). The chemical-specific dimensionless Henry's Law Constants (HLC) are multiplied by one-half (0.5) to account for reduced volatility of the contaminant under lower annual average soil temperatures of 10° Celsius in Michigan, relative to the measured HLCs reported at 25° Celsius (Howe et al., 1987). The soil-organic carbon partition coefficients (*K<sub>oc</sub>*) were calculated using regression analyses relating *K<sub>oc</sub>* values to octanol-water partition coefficients (*K<sub>ow</sub>*) as presented in EPA (1996a) guidance, and also in previous MDEQ (1998b) guidance.

The vapor concentration for contaminants in **groundwater** is assumed to be in equilibrium with the aqueous phase concentration. This equilibrium condition is a function of the dimensionless Henry's Law Constant (also adjusted for Michigan soil temperature). The concentration ratio relating the vapor phase concentration in the soil pore air, overlying the groundwater, to the total groundwater source concentration is given by the following equation:

$$CR_{source}^{gw} = (H' \times TAF) \times C_w \times 10^3 \text{ l} / \text{m}^3 \quad (7)$$

where,

<i>CR<sub>source</sub><sup>gw</sup></i>	(Ratio of vapor phase concentration to total groundwater source concentration)	= chemical-specific, (ug/m <sup>3</sup> )/(ug/l)*
<i>H'</i>	(Dimensionless Henry's law constant, where <i>H' = HLC × 41</i> )	= chemical-specific, unit less
<i>HLC</i>	(Henry's Law Constant)	= atm·m <sup>3</sup> /mol, chemical-specific
<i>TAF</i>	(Temperature adjustment factor)	= 0.5 (HLC adjusted to Michigan annual average soil temperature of 10° Celsius)
<i>C<sub>w</sub></i>	(Uniform concentration in groundwater)	= 1 ug/l

As in the soil calculation, a uniform unit concentration in water (1 ug/l) is assumed for purposes of back-calculating the GVIIC.

### **ATTENUATION COEFFICIENT**

The attenuation coefficient calculation is the core equation of the JEM. In general, the attenuation coefficient (*α*) is estimated as the ratio of contaminant vapor concentration in the building to the vapor concentration present at the source. To derive this ratio, the JEM accounts for certain key chemical and physical factors that influence vapor transport from the contaminant source into a building.

Transport of contaminant vapor from the source through the soil pores, or in the case of groundwater through the capillary fringe, to a building occurs as the result of molecular diffusion. Entry of contaminant vapors from the surrounding soil into the building may occur by diffusion, but can also occur through convective transport. Convective

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\* *CR<sub>source</sub><sup>gw</sup>* is expressed as a concentration ratio relating the vapor-phase contaminant concentration generated per unit contaminant concentration in groundwater (ug/l).



transport, or literally the drawing in of vapors, occurs as the result of pressure differences across the building shell. The JEM couples both diffusive and convective transport mechanisms into an analytical solution that predicts chemical-specific attenuation coefficients. Values of  $\alpha$  for soil can be derived for both steady state conditions (i.e., infinite contaminant source) and quasi-steady state conditions (i.e., given a finite source thickness). Values of  $\alpha$  for groundwater are calculated assuming only infinite source conditions. For infinite source conditions,  $\alpha$  is written as follows for soil and groundwater:

$$\alpha = \frac{\left[ \left[ \frac{D^{eff} A_b}{Q_{building} L_T} \right] \times \exp\left( \frac{Q_{soil} L_{crack}}{D^{crack} A_{crack}} \right) \right]}{\left[ \exp\left( \frac{Q_{soil} L_{crack}}{D^{crack} A_{crack}} \right) + \left[ \frac{D^{eff} A_b}{Q_{building} L_T} \right] + \left[ \frac{D^{eff} A_b}{Q_{soil} L_T} \right] \left[ \exp\left( \frac{Q_{soil} L_{crack}}{D^{crack} A_{crack}} \right) - 1 \right] \right]} \quad (8)$$

where,

$\alpha$	(Attenuation coefficient)	= unit less
$D^{eff} *$	(Effective diffusion coefficient)	= chemical-specific, $\text{cm}^2/\text{s}$
$D^{crack} *$	(Effective diffusion coefficient through crack)	= $\text{cm}^2/\text{s}$ , ( $D^{crack} = D_v^{eff}$ , see equation 9)
$A_b **$	(Area of enclosed space below grade)	= $1.96\text{E}+6 \text{ cm}^2$ (Residential) = $3.83\text{E}+6 \text{ cm}^2$ (Commercial/Industrial)
$Q_{building} **$	(Building ventilation rate)	= $1.51\text{E}+5 \text{ cm}^3/\text{s}$ (Residential) = $5.04\text{E}+5 \text{ cm}^3/\text{s}$ (Commercial/Industrial)
$L_{crack}$	(Building foundation thickness)	= 15 cm
$L_T$	(Source-building separation distance)	= 15 cm (soil) = 115 cm (groundwater-Residential) = 300 cm (groundwater- Commercial/Industrial)
$Q_{soil} **$	(Volumetric flow rate of soil vapor into the building)	= $0.81 \text{ cm}^3/\text{s}$ (Residential) = $2.10 \text{ cm}^3/\text{s}$ (Commercial/Industrial)
$A_{crack}$	(Total area of cracks below grade)	= $196 \text{ cm}^2$ (Residential) = $383 \text{ cm}^2$ (Commercial/Industrial)
$\exp(p)$	(The base of the natural logarithm raised to power p)	= $e^p$

\* When calculating the value of  $\alpha$  for soils, use the  $D_v^{eff}$  from equation 9. When calculating the value of  $\alpha$  for groundwater, use the  $D_T^{eff}$  from equation 10.

\*\* Calculated default inputs rounded to two significant figures for calculation of the criteria.

### **Effective Diffusion Coefficient**

The chemical-specific effective diffusion coefficients for the SVIIC ( $D_v^{eff}$ ) and GVIIC ( $D_T^{eff}$ ) describe the rate of vapor flow using simple Fickian diffusion modeling. Diffusion occurs in the both the pore air and pore water spaces through a tortuous path. This is accounted for in the calculation by applying a tortuosity factor defined by the Millington-Quirk model (Farmer et al., 1972) to the air- and water-filled porosity values. Therefore, **in soil** the rate of diffusion is dependent on the soil and chemical-specific characteristics as noted in the equation below:

$$D_v^{eff} = D_a \left( \theta_a^{3.33} / n^2 \right) + \frac{D_w}{H' \times TAF} \left( \theta_w^{3.33} / n^2 \right) \quad (9)$$

where,

$D_v^{eff}$	(Effective diffusion coefficient for vadose zone)	= chemical-specific, $\text{cm}^2/\text{s}$
$D_a$	(Diffusivity in air)	= chemical-specific, $\text{cm}^2/\text{s}$

$\theta_a$	(Soil air-filled porosity)	= 0.13 cm <sup>3</sup> /cm <sup>3</sup>
$n$	(Total soil porosity)	= 0.43 cm <sup>3</sup> /cm <sup>3</sup>
$D_w$	(Diffusivity in water)	= chemical-specific, cm <sup>2</sup> /s
$\theta_w$	(Soil water-filled porosity)	= 0.3 cm <sup>3</sup> /cm <sup>3</sup>
$H'$	(Dimensionless Henry's Law Constant, where $H' = HLC \times 41$ )	= chemical-specific, unit less
$HLC$	(Henry's Law Constant)	= atm-m <sup>3</sup> /mol, chemical-specific
$TAF$	(Temperature adjustment factor)	= 0.5 (HLC adjusted to Michigan annual average soil temperature of 10° Celsius)

Calculation of the effective coefficient for a contaminant *in groundwater* is more complex, since contaminant transport must be modeled across two different strata, the saturated (i.e., capillary fringe) and unsaturated (i.e., vadose zone) zones. The capillary fringe is a nearly saturated zone located directly above the top of the water table where groundwater is held within the soil pores at less than atmospheric pressure (Freeze and Cherry, 1979). The vadose zone, above the capillary fringe, has a lower soil moisture content and a greater amount of connected air-filled pore spaces. Chemical diffusivity through water is approximately four orders of magnitude lower than through air. To account for the variation in chemical diffusivity across these two zones, a total overall effective diffusion coefficient ( $D_T^{eff}$ ) is calculated as:

$$D_T^{eff} = \frac{L_T}{\left[ (h_v + L_{crack}) / D_v^{eff} \right] + (h_{cf} / D_{cf}^{eff})}$$

where,

(10)

$D_T^{eff}$	(Total overall effective diffusion coefficient)	= chemical-specific, cm <sup>2</sup> /s
$L_T$	(Source-building separation distance)	= 115 cm (Residential) = 300 cm (Commercial/Industrial)
$h_v$	(Thickness of vadose zone below enclosed space floor)	= 75 cm (Residential) = 260 cm (Commercial/Industrial)
$L_{crack}$	(Building foundation thickness)	= 15 cm
$D_v^{eff}$	(Effective diffusion coefficient through vadose zone; from equation 9 above)	= chemical-specific, cm <sup>2</sup> /s
$h_{cf}$	(Thickness of capillary fringe)	= 25 cm
$D_{cf}^{eff}$	(Effective diffusion coefficient through capillary fringe; from equation 11 below)	= chemical-specific, cm <sup>2</sup> /s

The thickness of the capillary fringe ( $h_{cf}$ ) is considered to be equal to the height of capillary rise in a tube for a specific soil material (e.g., sand, silt, and clay) and grain size. Although it is recognized that pore space openings and size vary considerably, such that capillary rise is not a straight line above the groundwater table, a standard value must be chosen for development of criteria.

Attachment A presents data for capillary rise values according to soil material and grain size from two separate reference sources. The data from the two sources show remarkable consistency. However, for simplicity, the most recent reference was chosen as the basis for the default  $h_{cf}$  value. Because the soil "materials" listed are not soil "types," the selection of which soil material to represent the generic loam soil is not straightforward. Gravel is not considered a soil material of loam, so "fine gravel" was eliminated from the analysis. Upon elimination of fine gravel values range from 4 to 750 cm, with a median or 50th percentile value of 50 cm and an upper-percentile value of 15 cm. However, it is not likely that "coarse sand" (15 cm) would predominate at many sites as an isotropic soil material, as assumed by the Johnson and Ettinger model. Because  $h_{cf}$  is a sensitive parameter for development of the GVIIC, a low to mid-range value was selected as a default value. A default value of 25 cm (10 inches) represented by "medium sand" was selected for  $h_{cf}$ .

This parameter may be modified for calculation of a facility-specific generic criterion provided that site data support a greater value for  $h_{cf}$ .

The effective diffusion coefficient to characterize vapor migration through the capillary fringe is determined as follows:

where,

$$D_{cf}^{eff} = \left[ D_a \left( \theta_{a,cf}^{3.33} / n^2 \right) \right] + \left[ \frac{D_w}{H' \times TAF} \left( \theta_{w,cf}^{3.33} / n^2 \right) \right] \quad (11)$$

$D_{cf}^{eff}$	(Effective diffusion coefficient for capillary fringe)	= chemical-specific, cm <sup>2</sup> /s
$D_a$	(Diffusivity in air)	= chemical-specific, cm <sup>2</sup> /s
$\theta_{a,cf}$	(Soil air-filled porosity in capillary fringe)	= 0.078 cm <sup>3</sup> /cm <sup>3</sup>
$D_w$	(Diffusivity in water)	= chemical-specific, cm <sup>2</sup> /s
$H'$	(Dimensionless Henry's Law Constant, where $H' = HLC \times 41$ )	= chemical-specific, unit less
$HLC$	(Henry's Law Constant)	= atm-m <sup>3</sup> /mol, chemical-specific
$TAF$	(Temperature adjustment factor)	= 0.5 (HLC adjusted to Michigan annual average soil temperature of 10° Celsius)
$\theta_{w,cf}$	(Soil water-filled porosity in capillary fringe)	= 0.352 cm <sup>3</sup> /cm <sup>3</sup>
$n$	(Total soil porosity)	= 0.43 cm <sup>3</sup> /cm <sup>3</sup>

As noted above, the capillary fringe is a predominantly saturated zone directly above the water table. The water content of the soil varies between drainage and wetting cycles, but is always less than completely water-filled which would equal the total porosity. This results from air entrapment in the pores during the wetting process (Gilham, 1984). Freijer (1994) found that vapor-phase diffusion coefficients were practically zero after soil samples were saturated with water, indicating that all remaining air-filled soil pores are disconnected and unavailable for vapor diffusion. However, as the air-filled porosity increased, the diffusion coefficients increased indicating the presence of connected air-filled pores. This minimum air-filled porosity at which the pores become interconnected is defined as the "air-entry pressure head." The air-entry pressure head corresponds with the top of the tension-saturated zone within the capillary fringe.

To account for the variation in air content throughout the capillary fringe, and for calculating contaminant transport via both liquid and vapor-phase diffusion, the  $\theta_{w,cf}$  is calculated at the air-entry pressure head ( $h$ ) according to the van Genuchten soil water retention curve equation (as cited in Carsel and Parrish, 1988) which is expressed as:

$$\theta_{w,cf} = \theta_r + \frac{\theta_s - \theta_r}{\left[ 1 + (\alpha h)^N \right]^M} \quad (12)$$

where the default values used to calculate  $\theta_{w,cf}$  are the mean values for the van Genuchten soil water retention parameters for the loam soil type, and are given in Attachment B.

$\theta_{w,cf}$	(Soil water-filled porosity in capillary fringe)	= 0.352 cm <sup>3</sup> /cm <sup>3</sup>
$\theta_r$	(Residual soil water content)	= 0.078 cm <sup>3</sup> /cm <sup>3</sup>
$\theta_s$	(Saturated soil water content)	= 0.43 cm <sup>3</sup> /cm <sup>3</sup>
$\alpha$	(Point of inflection in the water retention curve where $d\theta_w/dh$ is maximal)	= 0.036 cm <sup>-1</sup>
$h$	(Air-entry pressure head, $h = 1/\alpha$ )	= 27.778 cm
$N$	(van Genuchten curve shape parameter)	= 1.56 dimensionless
$M$	( $M = 1 - (1/N)$ )	= 0.359 dimensionless

Using the calculated value of  $\theta_{w,cf}$  within the capillary fringe at the air-entry pressure head, the air-filled porosity within the capillary fringe ( $\theta_{a,cf}$ ) is calculated as the total porosity ( $n$ ) minus  $\theta_{w,cf}$  (i.e.,  $0.078 \text{ cm}^3/\text{cm}^3$ ). Carsel and Parrish (1988) developed mean values of the van Genuchten soil water retention curve parameters for the 12 Soil Conservation Service (SCS) soil textural classifications. The database used to develop the mean values for the van Genuchten soil water retention curve parameters was developed from sampling data representing 42 states and ranged from sample population sizes of 46 to 1,183. With these data, defaults may be estimated for  $\theta_{w,cf}$  and  $\theta_{a,cf}$  for each soil classification.

#### **Effective Diffusion Coefficient Through Building Cracks ( $D^{crack}$ )**

The JEM assumes that the floor/wall cracks are filled with soil characterized by the density, porosity and moisture content of the underlying soil. Therefore, the effective diffusion coefficients through cracks ( $D^{crack}$ ) are equal to their corresponding  $D_v^{eff}$  as calculated in equation 9 above.

#### **Area of Building Below Grade ( $A_b$ )**

This parameter represents the cross-sectional area of the building that lies below ground surface. This value is therefore considered to represent the total subgrade building area (i.e., the area of the building structure that is below grade in contact with subsurface soil) through which vapors pass; it is sometimes referred to as the vapor infiltration area. For the generic residential scenario this value is equal to the total basement area, floor, and walls, that is below grade. It is also assumed that the foundation floor lies 200 centimeters (6.6 ft) below grade. Recall that the residential floorspace default value is  $1200 \text{ ft}^2$  ( $1.1\text{E}+6 \text{ cm}^2$ ;  $1 \text{ ft}^2 = 0.0929 \text{ m}^2 = 929 \text{ cm}^2$ ). Since the generic commercial/industrial building is a slab-on-grade construction, only the foundation floor is considered to lie below grade (i.e., 15 cm, or approximately 6 inches). The total floor space area for the commercial/industrial is  $4,000 \text{ ft}^2$ . Given these default values,  $A_b$  is calculated as follows:

$$A_b = L_b \times W_b + [2(L_F \times L_b) + 2(L_F \times W_b)] \quad (13)$$

where,

$A_b$	(Area of building below grade)	= $1.96\text{E}+6 \text{ cm}^2$ (Residential) = $3.83\text{E}+6 \text{ cm}^2$ (Commercial/Industrial)
$L_b$	(Building floor length)	= 1056 cm (Residential) = 1928 cm (Commercial/Industrial)
$W_b$	(Building floor width)	= 1056 cm (Residential) = 1928 cm (Commercial/Industrial)
$L_F$	(Depth below grade to bottom of enclosed space floor)	= 200 cm (Residential) = 15 cm (Commercial/Industrial)

#### **Building Ventilation Rate ( $Q_{building}$ )**

The building ventilation rate is expressed as the volumetric flow rate of air through the building. It is calculated as the product of the total building volume and an "air-exchange rate" (ACH):

$$Q_{building} = \frac{L_b \times W_b \times H_b \times ACH}{3600s / hr} \quad (14)$$

where,

$Q_{building}$	(Building ventilation rate)	= $1.51\text{E}+5 \text{ cm}^3/\text{s}$ (Residential) = $5.04\text{E}+5 \text{ cm}^3/\text{s}$ (Commercial/Industrial)
$L_b$	(Building floor length)	= 1056 cm (Residential) = 1928 cm (Commercial/Industrial)
$W_b$	(Building floor width)	= 1056 cm (Residential) = 1928 cm (Commercial/Industrial)
$H_b$	(Building height)	= 488 cm (Residential) = 244 cm (Commercial/Industrial)

<i>ACH</i>	(Indoor air exchange rate)	= 1/hour (Residential)
		= 2/hour (Commercial/Industrial)

The total building air volume for the generic residential and commercial/industrial scenarios are determined from the dimensions of these buildings given previously. Air exchange is considered the principle mechanism for diluting indoor air contaminant concentrations since contaminant levels in the outdoor air are assumed to be zero for purposes of generic criteria development. The ACH is expressed in terms of air changes per hour (i.e.,  $\text{h}^{-1}$ ), and is defined as the number of times in an hour that a volume of outside air equal to the internal volume enters the building (Mueller et al., 1988). In general, the ACHs of buildings are dependent on three processes: (1) mechanical or forced ventilation, (2) natural ventilation, and (3) infiltration. Mechanical ventilation is typically required for larger buildings where a certain amount of outdoor air is required for health and comfort. However, the Bureau of Construction Administrators (BOCA) National Mechanical Code requires an ACH of 0.35/hour for residential living areas of single and multiple private dwellings.

Natural ventilation refers to air moved into and out of a space through intentionally provided openings, such as windows and doors, or through nonpowered ventilators (e.g., operating fireplaces increase ventilation). Natural ventilation processes can vary broadly and depend on the weather, occupant behaviors, and activities. As a result, they are difficult to account for in developing a generic default value. Nonetheless, it is reasonable to assume that these processes increase ventilation above that required through mechanical means.

The ACH of a building is also influenced by infiltration, defined as the uncontrolled airflow through cracks or other unintentional openings. Infiltration of air is influenced by wind, temperature differences and operation of mechanical ventilation systems and appliances which all create pressure differences across the building envelope. Depending on the indoor-outdoor pressure differential, air flow will occur through any openings in the structure, which in turn affect the ACH. Much of the airflow is attributable to building construction methods and materials [e.g., building shape, surface area, orientation to prevailing winds, height (buoyancy of warm air), and location of doors and windows].

Scientific publications summarized in the *American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Fundamentals Handbook* (ASHRAE, 1993) indicate that residential ACH values can vary widely. Typical ACH values for housing in North America vary considerably, from tight housing construction with seasonal ACHs of about 0.2 to housing with ACHs of 2.0/hour. Individual studies (Grimsrud et al., 1983; Grot and Clark, 1981) summarized by ASHRAE and in the *EPA Exposure Factors Handbook* (1996) reported **geometric mean** ACH values of 0.53 +/- 1.71 and 0.9 +/- 2.13. The ACH of 0.53 represented energy efficient homes, while 0.9 ACH was for older, lower-income houses [Note: Geometric means are always less than arithmetic means].

Koontz and Rector (1995) compiled data from various projects (2,971 measurements) across the United States where perfluorocarbon tracer techniques (PFT) were used. Versar (1990) compiled these data into a PFT database. A review of Table 16-8 in the *EPA Exposure Factors Handbook* shows that very little information on ACH was obtained during the summer months from houses in northern climates. From this composite data, Koontz and Rector (1995) documented 0.45/hr ACH as the 50th percentile. The data are noted as being weighted to compensate for the geographic imbalance in locations where PFT measurements were taken. Data from Michigan are not included in this database, though several northern states were listed.

Single family detached homes without house tightening measures have ACHs ranging from 0.5 to 1.5/ hour (Mueller et al., 1988). The same article gives ranges for single-family attached houses, mobile homes, and apartments of 0.35 to 1, 0.3 to 1.5, and 0.3 to 0.9, respectively. It also states that ACHs for "typical residences" range between 0.7 to 1.1. Recent information on ACHs in residences and office buildings has been published by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) in an August 1996 Public Review Draft of Standard 62-1989R, *Ventilation for Acceptable Indoor Air Quality*. Pandian et al., (1993) reviewed data on 1,836 U.S. residences (locations not specified). ACH values were as low as 0.1/hr, with approximately half of the observations ranging from 0.35 to 2.35/hr with an arithmetic mean of 2.0/hr and standard deviation of 3.3/hr. ACHs changed considerably with seasons; mean values for fall (0.4/hr), winter (0.5/hr), spring (1.9/hr), and summer (5.4/hr) were reported. Mean ACH values in two-level homes (2.8/hr) were higher than in single-level homes.

Given the wide variability in ACH values, a default annual ACH of 1.0/hr was selected for residential land use. A default value of 2.0/hour was chosen for commercial/industrial. This is based on simple system rates for total supply air in a general office of approximately 1.0/hour (ASHRAE, 1996), and considering that ACHs above mechanical system requirements are expected from natural ventilation, infiltration, occupancy entrance, and egress. In general, choosing any reasonable value within the ranges noted above has only a modest effect on the final estimated indoor contaminant concentration (EPA, 1992a).

### **Building Foundation Thickness ( $L_{crack}$ )**

The default value of 15 cm (approximately 6 inches) is based on common construction code requirements.

### **Source-Building Separation Distance ( $L_T$ )**

The distance between the contaminant source in soil or groundwater and the building foundation floor for each generic land use scenario is illustrated in Figure 1 and 1a of the “Background and Conceptual Site Models” section. For generic application, contaminated soil must be assumed to lie immediately below the building foundation floor. Contaminant sources in groundwater are assumed to be located 115 cm from the **top** of the foundation floor for residential dwellings, and therefore 300 cm below ground surface considering that the bottom of the basement floor is 200 cm below grade. This shallow groundwater depth assumption is consistent with depths to groundwater in Michigan, while the 100 cm distance between the groundwater table (i.e., the source) and the bottom of the foundation is established to allow for seasonal fluctuations in the groundwater without direct entry of groundwater into the basement. Because the generic commercial/industrial building is a slab-on-grade, the  $L_T$  is 300 cm.

### **SOIL VAPOR CONVECTIVE FLOW RATE ( $Q_{soil}$ )**

As noted previously, the JEM incorporates both “diffusive” and “convective” mechanisms of vapor transport. The parameter,  $Q_{soil}$ , in the attenuation coefficient equation represents the convective flow rate of contaminant vapors in soil surrounding the subgrade floor and/or walls, to cracks in the building floor/walls. Although the transport of contaminant vapors through soil into buildings can occur solely by molecular diffusion, pressure-driven flow (i.e., convection) may be the principal means by which soil vapors enter buildings. In fact, convective flow of soil gas has been shown to be the dominant mechanism for radon transport into houses (Nazaroff et al., 1985; Nazaroff, 1988). In addition, modeling and field and experimental evidence with tracer gases and actual contaminants have also demonstrated the significance of convective vapor transport (Nazaroff et al., 1987; Little et al., 1992; Garbesi and Sextro, 1989). Calculation of the convective soil vapor flow rate is as follows:

$$Q_{soil} = \frac{2\pi\Delta P k_v X_{crack}}{\mu \ln[2Z_{crack} / r_{crack}]} \quad (15a)$$

where,

$Q_{soil}$	(Volumetric flow rate of soil vapor into the building)	= 0.81 cm <sup>3</sup> /s (Residential) = 2.10 cm <sup>3</sup> /s (Commercial/Industrial)
$\Delta P$	(Soil column-building dynamic pressure differential)	= 10 g/cm-s <sup>2</sup> (1 Pascal)
$k_v$	(Soil vapor permeability)	= 5E-9 cm <sup>2</sup>
$X_{crack}$	(Total floor/wall seam perimeter distance)	= 4224 cm (Residential) = 7712 cm (Commercial/Industrial)
$\mu$	(Vapor viscosity of air)	= 1.8E-4 g/cm-s
$Z_{crack}$	(Crack depth below grade to bottom of enclosed space floor)	= 200 cm (Residential) = 15 cm (Commercial/Industrial)
$r_{crack}$	(Crack radius)	= 0.05 cm

This equation is an analytical solution for vapor flow, solely from pressure-driven air flow, to an idealized cylinder buried at a fixed depth (  $Z_{crack}$  ) below ground surface. The length of the cylinder is equal to the building floor-wall seam perimeter (  $X_{crack}$  ). Therefore, the default values for  $X_{crack}$  are a function of the generic land use-based building floorspace area. Likewise, the default values for  $Z_{crack}$  correspond to the residential and commercial/industrial generic buildings described earlier (See also Figure 1 and 1a). The cylinder represents the portion or area of the building below grade through which vapors pass (i.e.,  $A_b$  ). The cylinder is considered to represent one of two potential types of openings for soil vapor entry as presented by Nazaroff (1988): (1) a floor-wall joint that is typically found with poured concrete floor and walls, or (2) a perimeter drain-tile system connected through an untrapped line to a basement sump. The radius of the floor-wall seam crack (  $r_{crack}$  ) is given by:

$$r_{crack} = \eta A_b / X_{crack} \quad (15b)$$

where,

$$\eta = A_{crack} / A_b, (0 \leq \eta \leq 1) \quad (15c)$$

The parameter  $r_{crack}$  is the product of the fixed crack to total area ratio ( $\eta$ ) and the hydraulic radius of the idealized cylinder, which is equal to the total area of the building below grade ( $A_b$ ) divided by the portion of the cylinder perimeter in contact with the soil vapor ( $X_{crack}$ ). The default value for  $\eta$  is given as a ratio of the total crack area ( $A_{crack}$ ) to the total area of the building below grade ( $A_b$ ). That is,  $\eta$  represents the fraction of the total subgrade structure area through which soil vapors pass. Grimsrud et al., (1983) empirically determined from leakage area experiments on houses that crack area ( $A_{crack}$ ) to total floorspace area ranges from 0.01 to 0.1 percent. Sample calculations for this range of  $\eta$  were completed to assess the reasonableness of the total crack area values generated for both generic land uses. The low end of the range,  $\eta = 0.01$  percent, was selected as a default as it corresponds to a reasonably conservative total open area of 30.4 in<sup>2</sup> (196 cm<sup>2</sup>) for the generic residential scenario. For consistency, an  $\eta$  of 0.01 percent is also used for the generic commercial/industrial criteria. Incorporating this default value into the above equation allows for calculation of the total crack area as follows:

$$A_{crack} = \eta A_b \quad (15d)$$

#### **Indoor-Outdoor Pressure Differential ( $\Delta P$ )**

Convective transport of soil contaminant vapors into buildings occurs as the result of depressurization (i.e., negative pressure) of the subgrade portion of the building relative to the pressure in the surrounding soil (Garbesi and Sextro, 1989). This indoor-outdoor pressure differential ( $\Delta P$ ) which drives the flow of vapors into the building is caused by meteorological, mechanical and occupant behavior factors. The meteorological factors include indoor-outdoor temperature differences ('stack effect'), wind loading on the building superstructure and barometric pressure changes. Examples of mechanical and occupant behavioral factors that lead to unbalanced ventilation include the operation of exhaust fans, ceiling fans, fireplaces, and oil/gas furnaces. The building type, design, materials, and workmanship (relative to the tightness of the construction) also influence building pressures.

ASHRAE (1993) indicates that wind driven pressure typically averages less than 2.5 Pascal's (Pa) [1 Pa = 10 g/cm-s]. A recent article by Fischer et al., (1996) estimated depressurization in a California home to be approximately 3 Pa due to average wind loading. Negative pressure produced from heating has been reported by Nazaroff et al. (1985). Values of  $\Delta P$  measured from February through May (15 samples) in a Chicago detached one-story house with a basement (characteristic of the residential generic) built in the 1950's ranged from 0.6 to 4.3 Pa with a mean of 2.3 Pa. These values are considered seasonal, as  $\Delta P$  values attributable to temperature in the nonheating season would be zero or positive. The effect of operating mechanical ventilation systems is reported to range from 3 to 6 Pa (ASHRAE, 1993). Lindmark and Rosen (1985) note that indoor atmospheres usually maintain a negative pressure of 0-2 Pa, though pressures three times this may be found in dwellings having mechanical ventilation and good insulation.

Collectively, this information indicates that some degree of negative pressure should be incorporated into the generic calculations as an annual default value. Characterizing the extent of depressurization for an annual period and representing the various factors is a highly uncertain process. Due to this uncertainty and the inability to estimate the simultaneous interactions of these factors, a default value for  $\Delta P$  of 1 Pa is chosen to preclude exaggerating the impact of this variable on the calculated criteria.

#### **Soil Vapor Permeability ( $k_v$ )**

Soil vapor or soil air permeability ( $k_v$ ) is a measure of the resistance to air flow in a porous medium; the greater the vapor permeability, the lower the resistance. Generally,  $k_v$  is a function of soil type and more specifically grain size and shape (EPA, 1995). As illustrated by Johnson and Ettinger (1991)  $k_v$  has a significant effect on the *convective* soil vapor flow rate into the building ( $Q_{soil}$ ), thus a large effect on the attenuation coefficient ( $\alpha$ ). Because  $k_v$  is one of the most sensitive parameters in the JEM, a conservative default value should be chosen for generic application and criteria development.

Since  $k_v$  is specifically related to soil directly adjacent to the subgrade portion of the building (i.e., soil within the 'zone of influence' as illustrated in Figures 1 and 1a), a slightly more conservative and representative soil type than the generic loam soil type was used to develop the default  $k_v$  value. These (backfill) soils typically have greater sand content to ensure adequate drainage of water from soil next to the foundation floor and walls. Therefore, "sandy loam" was selected as the soil type/classification for calculation of the default  $k_v$  value. The  $k_v$  was calculated using a procedure described by EPA (1995) and the soil physical characteristics data for sandy loam from Carsel and Parrish (1988). Attachment B lists the default input parameter values for the soil characteristics of sandy loam that are needed to derive the default  $k_v$  value. The default soil parameter input values are also provided in the attachment for the remaining 11 SCS soil textural classifications. The default  $k_v$  value is calculated as follows:

1. The "intrinsic" soil permeability is calculated as:

$$k_i = \left( \frac{k_s \times \mu_w}{\rho_w \times g} \right) \times \frac{1}{3600 \text{ s/hr}} \quad (16)$$

where,

$k_i$	Intrinsic soil permeability	= cm <sup>2</sup>
$k_s$	Saturated hydraulic conductivity	= 4.42 cm/hour (Carsel and Parrish, 1988)
$\mu_w$	Dynamic viscosity of water at 10°C	= 0.01307 g/cm-s
$\rho_w$	Density of water	= 0.999 g/cm <sup>3</sup>
$g$	Acceleration due to gravity	= 980.665 cm/s <sup>2</sup>

The calculated value for  $k_i$ , which is a property of the soil alone that varies with the size and shape of the connected pore openings, is therefore equal to 1.64E-8 cm<sup>2</sup>.

2. The relative vapor permeability is next calculated and is written as:

$$k_{rg} = (1 - S_{te})^{0.5} \times (1 - S_{te}^{1/M})^{2M} \quad (17)$$

where,

$k_{rg}$	Relative air permeability	= unit less
$S_{te}$	Effective total fluid saturation	= 0.644 unit less (see equation 18 below)
$M$	van Genuchten water retention parameter	= 0.471 unit less (Carsel and Parrish, 1988)

and,

$$S_{te} = \frac{\theta_w - \theta_r}{n - \theta_r} \quad (18)$$

where,

$\theta_w$	Soil water-filled porosity	= 0.3 cm <sup>3</sup> /cm <sup>3</sup>
$\theta_r$	Residual soil water content	= 0.065 cm <sup>3</sup> /cm <sup>3</sup> (Carsel and Parrish, 1988)
$n$	Total soil porosity	= 0.43 cm <sup>3</sup> /cm <sup>3</sup>

Therefore,  $k_{rg} = 0.373$ .



3. Finally, the soil air permeability ( $k_v$ ) is calculated as:

$$k_v = k_i \times k_{rg} \quad (19)$$

$$k_v = \underline{6.1\text{E-}9 \text{ cm}^2}$$

To avoid implied precision in a parameter that may vary widely within a small area, the default  $k_v$  value is set at  $5\text{E-}9 \text{ cm}^2$  (i.e., the mid-value between  $1\text{E-}8$  and  $1\text{E-}9 \text{ cm}^2$ ) for calculation of the generic GVIIC and SVIIC.

The above procedure used to derive the default  $k_v$  value for soil in contact with the subgrade portion of the building assumes homogeneous soils. Though this may be a conservative assumption in some cases, it is equally important to note that the equations do not account for preferential vapor migration that may occur as a result of soil fractures, vegetation root pathways, or the effects of a gravel layer or backfill that may increase the vapor permeability of these soils, thus increasing the overall soil gas entry flow rate into the building ( $Q_{soil}$ ).

### **FINITE SOURCE SOIL VOLATILIZATION TO INDOOR AIR INHALATION CRITERIA**

Equation 8 above, calculation of the attenuation coefficient ( $\alpha$ ), does not account for depletion of the contaminant source over time. That is, an infinite contaminant source is assumed. Johnson and Ettinger (1991) provide a finite source method that can be used if the vertical thickness of soil contamination is known. A time-averaged finite source attenuation coefficient,  $\alpha$ , can be calculated to account for depletion of the contaminant vapor source over time. Calculations performed assuming a two-meter source thickness in the equations below revealed negligible differences between the finite and infinite SVIIC for the majority of chemicals. Notable differences existed for only the highly volatile chemicals (approximately 12 chemicals). Therefore, finite generic SVIIC are not provided in the Part 201 Integrated Table.

**The method outlined below cannot be used for groundwater.** Depletion of a groundwater contaminant source over time is more difficult to determine due to the continuous movement of groundwater and the uncertainty of the source characteristics.

Although many processes can contribute to source fluctuations over time, such as biodegradation, chemical interaction and transport away from the source, only the latter is currently incorporated into the finite source method presented below. Implicit in this approach is the assumption that depletion occurs first from contaminant nearest the building floor, and a hypothetical depletion zone increases in thickness over time (Johnson and Ettinger, 1991). Since the JEM considers vapor migration in one dimension, it is important that the vertical thickness of the source be adequately characterized throughout the facility. Depending on the vertical thickness of the contamination, contaminant of concern, and land use-specific exposure period, the time required for source depletion ( $\tau_D$ ) may be less than the time period over which exposure is averaged. The time required to deplete a finite source ( $\tau_D$ ) of thickness  $\Delta H_c$  is given as:

$$\tau_D = \frac{\left[ \Delta H_c / L_T^0 + \beta^2 \right] - \beta^2}{2\psi} \quad (20a)$$

where,

$\Delta H_c$	(Thickness of soil contamination)	= site-specific, cm
$L_T^0$	(Source-building separation at time (t) = 0)	= site-specific, cm

and,

$$\beta = \left( \frac{D_v^{eff} A_b}{L_T^0 Q_{soil}} \right) \left[ 1 - \exp \left( - \frac{Q_{soil} L_{crack}}{D_{crack} A_{crack}} \right) \right] + 1 \quad (20b)$$

and,

$$\psi = \left[ \frac{D_v^{eff} CR_{source}}{(L_T^0)^2 \rho_b C_s} \right] \times 10^3 \text{ g/kg} \times 10^{-6} \text{ m}^3/\text{cm}^3 \quad (20c)$$

where,

$D_v^{eff}$	(Effective diffusion coefficient through vadose zone)	= chemical-specific (cm <sup>2</sup> /s)
$CR_{source}^{soil}$	(Ratio of vapor phase concentration to total soil source concentration)	= chemical-specific, (ug/m <sup>3</sup> )/(ug/kg); (see Equation 6)
$A_b$	(Area of enclosed space below grade)	= 1.96E+6 cm <sup>2</sup> (Residential) = 3.83E+6 cm <sup>2</sup> (Commercial/Industrial)
$Q_{soil}$	(Volumetric flow rate of soil vapor into the building)	= 0.81 cm <sup>3</sup> /s = 2.10 cm <sup>3</sup> /s
$L_{crack}$	(Building foundation thickness)	= 15 cm
$D^{crack}$	(Effective diffusion coefficient through crack)	= cm <sup>2</sup> /s, ( $D^{crack} = D_v^{eff}$ , see equation 9)
$A_{crack}$	(Total area of cracks below grade)	= 196 cm <sup>2</sup> (Residential) = 383 cm <sup>2</sup> (Commercial/Industrial)
$\rho_b$	(Dry soil bulk density)	= 1.5 g/cm <sup>3</sup>
$C_s$	(Initial average contaminant level in soil at time (t) = 0)	= 1 ug/kg

If the exposure averaging period ( $\tau$ ) is greater than or equal to  $\tau_D$  the average building indoor vapor contaminant concentration to the soil vapor phase source concentration ratio ( $CR_{building}$ ) is adjusted for incorporation into equation 1 or 2, as follows:

$$CR_{building} = \left[ \left( \frac{\rho_b C_s \Delta H_c A_b}{\tau} \right) \times 10^{-3} \text{ kg/g} \right] \times \left( \frac{1}{Q_{building}} \right) \times 10^6 \text{ cm}^3/\text{m}^3 \quad (21)$$

where,

$CR_{building}$	(Ratio of indoor vapor concentration to soil or groundwater vapor source concentration)	= chemical-specific, (ug/m <sup>3</sup> )/(ug/kg)
$\tau$	(Exposure averaging period)	= 9.5E+8 s (Residential, i.e., 30 years) = 6.6E+8 s (Commercial/Industrial)
$Q_{building}$	(Building ventilation rate)	= 1.51E+5 cm <sup>3</sup> /s (Residential) = 5.04E+5 cm <sup>3</sup> /s (Commercial/Industrial)

Though unnecessary for calculation of finite source SVIIC, the long-term average finite source attenuation coefficient may be derived as follows:

$$\alpha = \frac{\rho_b C_s \Delta H_c A_b}{Q_{building} CR_{source}^{soil} \tau} \left( \frac{L_T^0}{\Delta H_c} \right) \left[ (\beta^2 + 2\psi\tau)^{1/2} - \beta \right] \times 10^{-3} \text{ kg/g} \times 10^6 \text{ cm}^3/\text{m}^3 \quad (22)$$

### **APPLICATION AND IMPLEMENTATION**

The purpose of the Part 201 generic GVIIC and SVIIC is to identify sites where contaminant concentrations in groundwater or soil may be sufficient to pose unacceptable inhalation risks from the intrusion and accumulation of contaminant vapors in buildings. These values can be used for determining whether a property is a facility, and are relevant in determining the adequacy of a RAP.

The criteria provided in the Part 201 Integrated Table are generated from a series of calculations which make a number of generic assumptions related to the contaminant source, soil, groundwater and building characteristics, and human exposure potential. Figures 1 and 1a (the generic CSMs) illustrate some of these assumptions used in the development of the generic criteria. The quantitative method and default assumptions provide reasonably conservative criteria. As a result, further evaluation of indoor air inhalation risks is not required at sites with concentrations less than these values, unless one or more of the following conditions exist, in which case, the generic GVIIC and/or SVIIC do not apply and a site-specific evaluation must be conducted.

- A structure is present or is planned for construction that uses materials at or below grade, such as soil or stone for floors or walls, that does not provide an equivalent limitation on vapor infiltration as is provided by poured or concrete block floors and walls.
- A sump is present that is not completely encased from the surrounding soil by construction materials.
- For the GVIIC, the highest groundwater table elevation, considering seasonal variation, is less than three meters below grade, or there is direct entry of contaminated groundwater into the building, such as seepage through the foundation floor, walls, drains, or a sump opening.

In all cases, it is important that users consult with ERD toxicologists when addressing facility situations that are NOT represented by the generic assumptions inherent to these criteria. For example, these criteria may not be appropriate at facilities where site investigations reveal that foundation floors and/or walls are in poor condition, or other openings exist such as around utility line entry points.

#### GVIIC Application

The groundwater volatilization to indoor air pathway is relevant for both groundwater in an aquifer and groundwater not in an aquifer. For situations where the groundwater table elevation is greater than three meters below grade, the Part 201 generic GVIIC are applicable at all depths within the groundwater saturated zone. If the groundwater table is less than three meters below grade, site-specific criteria must be determined, and would be applicable at all depths within the groundwater saturated zone. In addition, it must be demonstrated that seasonal fluctuation in the groundwater table will not result in the groundwater table contacting the building. If the quantity of groundwater encountered at a depth below grade of less than three meters is small, professional judgment can be used to determine if the GVIIC pathway is relevant for that shallow groundwater.

#### Facility-Specific Generic Land Use Closures

Due to wide variation in site-specific soil characteristics and exposure settings, it is probable that the generic assumptions may not accurately represent the conditions at certain sites. For these cases, facility-specific values may be used in place of the generic assumptions and still allow for generic closures under Section 20120a(1)(a), (b), and (d). Any of the following three soil parameters listed below may be substituted in place of the generic values for a generic closure:

- Soil vapor permeability ( $k_v$ )
- Dry soil bulk density ( $\rho_b$ )
- Soil organic carbon content ( $f_{oc}$ )

Dry soil bulk density ( $\rho_b$ ) can be determined by weighing a thin-walled tube soil sample (e.g., Shelby tube) of known volume and subtracting the tube weight to estimate "field" bulk density (ASTM, 1994). A moisture content determination (ASTM, 1992) is then performed on a subsample of the tube sample to adjust field bulk density to dry bulk density. Soil organic carbon content ( $f_{oc}$ ) is determined by burning off soil carbon in a controlled-temperature oven (Nelson and Summers, 1982).

The default soil water-filled porosity ( $\theta_w$ ) and soil air-filled porosity ( $\theta_a$ ) values represent soil not covered by a building. Since infiltration of water into soil (soil moisture recharge) below a building will be reduced for most structures,  $\theta_w$  and  $\theta_a$  should not be made less conservative. Therefore, modification of  $\theta_w$  and  $\theta_a$  is not appropriate.

Facility-specific generic closures can also be obtained by replacing the generic default values with site-specific values for the following parameters:

- Chemical-specific Temperature Adjustment Factor ( $TAF$ ) for the Henry's Law Constant

- Source-building foundation separation distance (  $L_T$  ) **for GVIIC only** (Generic building assumptions cannot be changed)
- Vertical thickness of capillary fringe (  $h_{cf}$  ) **for GVIIC only**
- Vertical thickness of soil contamination (  $\Delta H_c$  ) **for finite source SVIIC only**

Finally, an “**overall**” effective diffusion coefficient for the vadose zone (  $D_{v,T}^{eff}$  ) may be calculated to demonstrate compliance with the generic GVIIC, thus obtain a facility-specific generic closure. In general, the vadose zone may be composed of several soil types with varying moisture contents and porosities. Therefore, a  $D_{v,T}^{eff}$  may be calculated for sites where several distinct soil layers between the groundwater table and building floor have been sufficiently characterized. The value calculated for  $D_{v,T}^{eff}$  from the equation below is then substituted in place of the  $D^{eff}$  in equation 8:

$$D_{v,T}^{eff} = \frac{L_T}{\sum_{i=0}^n L_i / D_i^{eff}} \quad (23)$$

where,

$D_{v,T}^{eff}$	(Overall effective diffusion coefficient for the vadose zone)	= cm <sup>2</sup> /s
$L_T$	(Distance between the groundwater table and bottom of the building floor)	= cm
$L_i$	(Vertical thickness of soil layer i)	= cm
$D_i^{eff}$	(Effective diffusion coefficient across soil layer i – See equation 9)	= cm <sup>2</sup> /s

Supporting documentation for all facility-specific parameter value(s) must be provided in the RAP.

**Modification of the generic building or human exposure assumptions cannot be made for a facility-specific generic closure.** Modification of these assumptions will require closure under Section 20120a(2), such that proper administrative mechanisms are in place to assure that future site conditions will remain consistent with the site-specific human exposure and/or building assumptions.

#### Options for Demonstrating Compliance

There are a number of approaches that may be considered to demonstrate protection against unacceptable indoor air inhalation risks once it is determined that one or more of the individual facility sample concentrations do not meet the relevant land use-based generic GVIIC and/or SVIIC.

More detailed modeling approaches may be used to satisfy the requirements of a facility-specific generic closure. Justification must be provided describing why the proposed model is more appropriate to the site in question than the JEM. The proposed model must be documented and shown to be mathematically sound, and account for both diffusive and convective vapor transport mechanisms.

Statistical evaluation of site data may be conducted to demonstrate compliance with the generic criteria. Statistical analysis of site data must not encompass areas larger than the relevant generic land use building footprint size (i.e., residential - 1,200 ft<sup>2</sup>; commercial/industrial - 4,000 ft<sup>2</sup>). In addition, if there are groundwater and soil sample concentrations greater than water solubility or C<sub>sat</sub> concentrations, respectively, statistical analysis is not appropriate since the equilibrium partitioning equations of the JEM are not valid at such levels.

Soil gas measurements may also be used to demonstrate a facility-specific generic closure. If collected properly, soil gas sampling should more accurately represent the soil vapor contaminant concentrations that are subject to the convective transport mechanisms attributable to the soil vapor permeabilities and building pressure influences on the surrounding soil. Soil gas measurements/data cannot be incorporated into the generic equation framework presented above, since soil gas measurements are reported as concentrations whereas “concentration ratios” are used in the generic approach for purposes of back-calculating acceptable soil and groundwater concentrations. A methodology,

however, has been developed through rearrangement of aspects of the JEM and risk assessment equations to calculate chemical-specific soil gas concentrations protective of unacceptable indoor air inhalation risks (Attachment C). This method is only applicable for demonstrating compliance with the SVIIC; a method may be developed in the future to demonstrate compliance with the generic GVIIC.

Due to the heterogeneity of physical soil characteristics, it is expected that soil gas concentrations will vary considerably with location and time of collection. As a result, it is necessary to collect soil gas samples at various points around the building, and to conduct a minimum of two sampling events. The use of soil gas probes is recommended, with a minimum of two sampling points on each side of the building. One additional sample should be obtained from directly beneath the building, nearest to center as possible. EPA (1990) indicates that this sample size is sufficient for calculating the mean concentration within 20 percent of the 95 percent upper confidence level. ASTM (1997) provides guidance for conducting soil gas monitoring.

To determine the resulting soil vapor infiltration rate, it is necessary to obtain measurements of the soil vapor permeability ( $k_v$ ) at each of the probe locations. Values of  $k_v$  will indicate whether infiltration of vapors into the building is likely to occur by diffusion or convection. Probes should be installed so that the probe tips are between 50 and 100 cm from the floor or basement wall. For generic commercial/industrial buildings that are assumed to be slab-on-grade, probes should be positioned at an angle to reach under the building.

#### "Limited" Land Use Closure Options

A party may elect not to comply with the generic GVIIC or SVIIC, but show through an adequate indoor air monitoring plan that contaminant concentrations in the building are below acceptable levels. The acceptable indoor air concentration for a given contaminant is determined by eliminating the parameter  $CR_{building}$  from equations 1 through 4.

An adequate indoor air sampling/monitoring plan is one where measurements are obtained on the day(s) that represent average conditions for the structure being tested. It is recommended that monitoring be conducted on several "different" days under conditions that approximate the range of most common meteorological and building operating conditions. Best monitoring conditions exist when the indoor air temperature is at least 10°F higher than outside and wind speeds are steady and greater than five miles per hour. Monitoring should be avoided if considerable precipitation or barometric pressure changes have occurred within 12 hours of the sampling event (EPA, 1992b).

Unfortunately, monitoring indoor air alone is only useful if it shows negative results, as detections above acceptable indoor air concentrations elicit a need to identify the source of the contamination. It should not be concluded that detection of unacceptable indoor air concentrations is the result of soil contaminant vapor infiltration unless ambient air measurements and evaluation of household sources are ruled out. Optimally, indoor air monitoring combined with ambient air and soil gas measurements provide the necessary database for assessing the potential impact of subsurface contamination on the indoor air quality of buildings. Sampling of contaminant concentrations in these three areas should take place within a 12-hour period, since significant changes in barometric pressure or measurable rainfall could affect the results. Further guidance on indoor air sampling protocols and analyses are provided in EPA (1990a, 1990b, and 1992a).

Installing and maintaining vapor barriers is another means for obtaining a limited land use closure. Vapor barriers may consist of simple measures such as sealing off soil vapor entry routes or engineered mitigation technologies designed to divert or vent contaminant vapors away from the building. One may also opt to allow contaminant vapors to enter but control contaminant concentrations at acceptable levels through ventilation or dilution techniques. Details of these mitigation strategies can be found in EPA (1993).

In some cases, it may be preferable to limit exposure through restrictions on property use. Deed restrictions can be placed on the property in question to prevent construction of buildings.

An alternative to complying with the GVIIC at all groundwater depths may be possible in certain situations if reliable controls and monitoring are implemented to assure that upward migration of groundwater contaminants does not occur.

A facility-specific evaluation to document that conditions at a facility do not result in an unacceptable exposure may be based on demonstration of compliance with Act No. 174 of the Public Acts of 1974, as amended, being Section 408.1001 et seq. of the Michigan Compiled Laws, and known as the Michigan Occupational Health and Safety Act, and the rules promulgated pursuant to that Act. This approach would be handled as a site-specific closure in accordance with Section 20120a(2), and requires a restrictive covenant filed with the deed in a manner analogous to

a limited closure pursuant to Section 20110a(1). Site-specific criteria developed pursuant to this provision shall apply when all of the following conditions are satisfied:

- a) The risk being evaluated results from inhalation by workers of hazardous substances in indoor air within an active commercial or industrial workplace that is regulated by the Michigan Occupational Safety and Health Act, and the rules promulgated pursuant to that Act.
- b) The exposure to hazardous substances from environmental contamination is a portion of the exposure to which workers are otherwise subject from process-related sources of the same hazardous substance.
- c) The risk to the non-worker population, if any, from inhalation of indoor air at the facility has been evaluated according to risk assessment methods acceptable to the department, and the risk is not unacceptable on the basis of the risk management objectives set forth in Section 20120a of the Act.

#### Chemicals of Concern

Generic criteria are **not** presented for all hazardous substances in the Part 201 Generic Cleanup Criteria Tables. This is because some substances either do not volatilize (elemental inorganics) or volatilize at such low levels that their vapor phase concentration would not exist at a sufficient level to pose a health risk. These chemicals have the notation "NLV", not likely to volatilize, in the Part 201 Generic Cleanup Criteria Tables. Chemicals of concern for this pathway were identified as those having a Henry's Law Constant equal to or greater than  $1\text{E-}5 \text{ atm}\cdot\text{m}^3/\text{mol}$  at standard temperature and pressure (Jury et al., 1983; Jury et al., 1984a,b,c; Thomas, 1982). Chemicals that are designated "ID", insufficient data, are lacking one or more of the chemical-specific property values needed to calculate a criterion.

#### Soil Saturation and Water Solubility Limits

The generic SVIIC default to the soil saturation limit when the generic SVIIC is greater than Csat. Therefore, it is necessary to compare the SVIIC with its corresponding Csat value. The Csat values published in the Part 201 Generic Cleanup Criteria Tables differ slightly from the values documented in the January 17, 1997 memorandum containing the *Soil Saturation Screening Concentrations: Technical Support Document* (TSD). This is due to the use of soil physical parameter default values representative of **subsurface** soil conditions instead of **surficial** conditions, and incorporation of the soil temperature adjustment factor (TAF) to the HLCs to be consistent with the approach used to calculate the GVIIC and SVIIC. Generic GVIIC greater than the water solubility default to the water solubility value as the applicable criterion. These default approaches are necessary since the equilibrium partitioning aspects of the criteria calculations (i.e.,  $CR_{source}$ ) are not applicable at concentrations greater than Csat and water solubility for soil and groundwater contaminants, respectively.

This document is intended to provide guidance to ERD staff to foster consistent application of Part 201, Environmental Remediation, of the Natural Resources and Environmental Protection Act, 1994 PA 451, as amended, and associated Administrative Rules. This document and matters addressed herein are subject to revision.

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## Attachment A

### Thickness of capillary fringe - $h_{cf}$

Table 1. Height of capillary rise in sample having virtually the same porosity, 41 percent, after 72 days (Source: Ground-Water Hydraulics, S.W. Lohman, Geological Survey Professional Paper 708).

Material	Grain Size, mm	Capillary Rise, cm
Fine gravel	5-2	2.5
Very coarse sand	2-1	6.5
Coarse sand	1-0.5	13.5
Medium sand	0.5-0.2	24.6
Fine sand	0.2-0.1	42.8
Silt	0.1-0.05	105.5
Silt	0.05-0.02	200 <sup>a</sup>

<sup>a</sup> Still rising after 72 days.

Table 2. Capillary rise in sediments (Source: Applied Hydrogeology, 3rd Edition, Prentice Hall, C.W.Fetter).

Material	Grain Size, mm	Capillary Rise <sup>b</sup> , cm
Fine gravel	5	1.5
Very coarse sand	2	4
Coarse sand	0.5	15
Medium sand	0.3	25
Fine sand	0.15	50
Very fine sand	0.075	100
Coarse silt	0.025	300
Fine silt	0.008	750

<sup>b</sup> Capillary rise ( $H_c$ ) values calculated as:

$$H_c = \frac{2\sigma \times \cos\lambda}{\rho_w \times g \times R}$$

where,

$\sigma$	surface tension of water	= 73 g/s <sup>2</sup>
$\lambda$	angle of meniscus with capillary tube walls	= 0 (Therefore Cos of lambda = 1)
$\rho_w$	density of water	= 1 g/cm <sup>3</sup>
$g$	acceleration due to gravity	= 980 cm <sup>2</sup>
$R$	radius of capillary tube	= 0.2 x assumed grain diameter

## Attachment B

**Mean values of the van Genuchten soil moisture retention and relative permeability parameters for the U.S. Department of Agriculture soil types (EPA, 1995; modified from Carsel and Parrish, 1988)**

Soil Texture (USDA)	Saturated Hydraulic Conductivity (cm/hr)	Saturated Water Content $\theta_s$	Residual Water Content $\theta_r$	van Genuchten Parameters			Number of Samples**
				$\alpha$ (1/cm)	N	M	
Clayey Soil*	0.2	0.38	0.068	0.008	1.09	0.083	400
Clay Loam	0.26	0.41	0.095	0.019	1.31	0.237	364
<b>Loam</b>	1.04	0.43	0.078	0.036	1.56	0.359	735
Loamy Sand	14.59	0.41	0.057	0.124	2.28	0.561	315
Silt	0.25	0.46	0.034	0.016	1.37	0.27	82
Silt Loam	0.45	0.45	0.067	0.02	1.41	0.291	1093
Silty Clay	0.02	0.26	0.07	0.005	1.09	0.083	374
Silty Clay Loam	0.07	0.43	0.089	0.01	1.23	0.187	641
Sand	29.7	0.43	0.045	0.145	2.68	0.627	246
Sandy Clay	0.12	0.38	0.1	0.027	1.23	0.187	46
Sandy Clay Loam	1.31	0.39	0.1	0.059	1.48	0.324	214
<b>Sandy Loam</b>	4.42	0.41	0.065	0.075	1.89	0.471	1183

\* Clay soil refers to agricultural soil with <60% clay.

\*\* Number of samples as indicated with minor exceptions: see Carsel and Parrish (1988).

Note: Loam soil type bolded to indicate parameters values used to calculate the water-filled porosity ( $\theta_{w,cf}$ ) and air-filled porosity ( $\theta_{a,cf}$ ) default values for the capillary fringe. Sandy loam soil parameter values are used to calculate the soil vapor permeability ( $k_v$ ) default value.

## Attachment C

### Method for Calculating Chemical-Specific Soil Gas Concentrations Protective of Unacceptable Indoor Air Inhalation Health Risks: An Option for Demonstrating Compliance with SVIIC

As an example, the acceptable indoor air vapor concentration,  $C_{building}$ , for the residential land use exposure assumptions for carcinogenic chemicals is: (Note that the adjusted inhalation rate, AIR, parameter would need to be multiplied in the numerator for commercial/industrial land use calculations)

$$C_{building} = \frac{TR \times AT}{IURF \times EF \times ED} = \frac{ug}{m^3}$$

where,

$TR$	(Target risk)	= 1E-5
$AT$	(Averaging time)	= 25,550 days (70 x 365)
$IURF$	(Inhalation unit risk factor)	= chemical-specific, (ug/m <sup>3</sup> ) <sup>-1</sup>
$EF$	(Exposure frequency)	= 350 days/year (Residential), = 245 days/year Commercial/Industrial)
$ED$	(Exposure duration)	= 30 years (Residential) = 21 years (Commercial/Industrial)

The acceptable soil gas (vapor) concentration,  $C_{source}$ , can be back-calculated given that:

$$C_{building} = \alpha \times C_{source}$$

where,

$\alpha$	(Attenuation coefficient)	= unit less (see equation 8)
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Since the contaminant source is assumed to lie directly below the foundation for generic SVIIC calculations, the source-to-building separation distance approaches zero and  $\alpha$  can be approximated by  $Q_{soil}/Q_{building}$ . Therefore,

$$C_{building} = \frac{Q_{soil}}{Q_{building}} \times C_{source}$$

where,

$Q_{soil}$	(Volumetric flow rate of soil vapor into the building)	= 0.81 cm <sup>3</sup> /s (Residential) = 2.10 cm <sup>3</sup> /s (Commercial/Industrial)
$Q_{building}$	(Building ventilation rate)	= 1.51E+5 cm <sup>3</sup> /s (Residential) = 5.04E+5 cm <sup>3</sup> /s (Commercial/Industrial)

Algebraically,

$$C_{source} = C_{building} \times \frac{Q_{building}}{Q_{soil}}$$

The generic land use-specific default assumptions for  $Q_{soil}$  and  $Q_{building}$  must be used to derive the correct soil gas concentration,  $C_{source}$ , in units of ug/m<sup>3</sup>, that corresponds to the generic GVIIC and SVIIC. These units can be converted to ppm by volume (ppmv), if necessary, for comparison to site-specific soil gas measurements using the ideal gas law as follows:

$$SG = \frac{R \times T}{p \times mw} \times C_{source} \times 10^{-6} \text{ g / ug}$$

where,

SG	Soil gas concentration	= cm <sup>3</sup> /m <sup>3</sup> or ppmv (chemical-specific)
R	Universal gas constant	= 82.05 atm-cm <sup>3</sup> /mol-K
T	Absolute temperature	= 293.16 K (20° C)
p	Absolute pressure of gas	= 1 atm
mw	Molecular weight	= chemical-specific (g/mol)

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## **Appendix 2**

**October 29, 1999 Correspondence to the Michigan Environmental Science Board  
from Governor John Engler**

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STATE OF MICHIGAN

OFFICE OF THE GOVERNOR

LANSING

October 29, 1999

JOHN ENGLER  
GOVERNOR

Dr. Lawrence J. Fischer, Chair  
Michigan Environmental Science Board  
P.O. Box 30680  
Lansing, MI 48909

Dear Dr. Fischer:

The Department of Environmental Quality (DEQ) is engaged in the development of generic cleanup criteria to implement the provisions of Part 201, Environmental Remediation, of the Natural Resources and Environmental Protection Act, 1994 PA 451, as amended. In 1995 amendments to Part 201 were enacted that require the DEQ to use "reasonable and relevant" exposure pathways in developing generic, land use based cleanup criteria (MCL 324.20120a(3)). The DEQ has identified inhalation of volatile hazardous substances that migrate into indoor air from contaminated soil and groundwater as a reasonable and relevant exposure pathway. Since early 1997, the DEQ has been working on development of scientifically sound and reasonable generic cleanup criteria for indoor air contaminants attributable to migration from environmental contamination. The DEQ's experience supports the concept that vapors will move passively through soil and be drawn into interior spaces because of the pressure differentials which exist between the two environments. In addition, there is considerable evidence published in the scientific literature that supports soil-gas transport and entry into buildings as a common phenomenon (i.e., volatile hazardous substances move as a gas through soil and building foundations and enter habitable spaces).

The DEQ has proposed administrative rules that describe conditions under which the indoor inhalation pathway is deemed relevant and that set forth algorithms for calculation of generic criteria. Scientifically supportable and practical cleanup criteria are essential to the protection of public health and safety, and to the functioning of the cleanup program. Further, a rational and credible cleanup program contributes to the success of our efforts to reuse contaminated property throughout the state. Therefore, I request that the Michigan Environmental Science Board (MESB) evaluate the DEQ's approach to



Dr. Lawrence Fischer  
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October 29, 1999

evaluating these risks (as described in the document entitled, "Part 201 Generic Groundwater and Soil Volatilization to Indoor Air Inhalation Criteria -- Technical Support Document") and determine whether it provides a scientifically and technically defensible strategy for the development of generic cleanup criteria for the indoor air inhalation exposure pathway. If the MESB determines that there are other equally defensible approaches for evaluating risk in this pathway, its recommendations in that regard would be welcome.

I am directing the DEQ to cooperate fully with the MESB's review of this important issue. I encourage the MESB to seek input from other outside interests and experts as it deems necessary. I would appreciate the MESB providing me with its recommendations as soon as possible.

Thank you for your continuing service to the citizens of Michigan.

Sincerely,



John Engler  
Governor

JE/mhem

cc: Mr. Russell J. Harding, Director, DEQ  
Mr. Keith G. Harrison, Executive Director, MESB  
Mr. Alan J. Howard, DEQ





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Knapps Centre, Suite 340, P.O. Box 30680, Lansing, Michigan 48909-8180**

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